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GEOPHYSICAL EXPLORATION COMES OF AGE*

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ABSTRACT

The oil industry throughout the world last year invested about $325,000,000 in geophysical exploration for oil. This marks a phenomenal growth of the science since its inception less than three decades ago. The commercial acceptance of geophysics is justified by its success in eliminating many wasteful "dry holes" in drilling for oil. Applications in the search for other minerals show encouraging gains. The paper (1) reviews briefly the history and growth of geophysical exploration, especially as related to oil-finding, and of the Society of Exploration Geophysicists; (2) discusses the present technical status and world-wide industrial scope; and (3) attempts to peer into the future to catch a glimpse of future developments and prospects.

My title, "Geophysical Exploration Comes of Age," has been chosen to commemorate the twenty-first anniversary of the Society which I have the honor to represent at this great meeting. Another birthday is not, of itself, an event of any particular importance. On the other hand, the twenty-first birthday of an organization, as well as of an individual, has traditionally been the time to stop to review the past, to take stock of the present, and to consider the prospects for the future. Following this precedent, I shall attempt (1) to review the growth of geophysical exploration, particularly in the United States but not ignoring foreign developments; (2) to point out where geophysical exploration stands today; and (3) to try to peer into the future to catch a glimpse of what may lie ahead.

In terms of the history of science and technology, geophysical prospecting is very young. It is true that important deposits of iron ore were discovered by magnetic surveys as long as a hundred years ago. But we need not stop to consider that ancient phase. The modern age of geophysical prospecting can

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fairly be said to have begun in 1915 when an Eotvos torsion balance survey successfully extended the deep flanks of the Egbell structure in Czechoslovakia.[1] This was apparently the first deliberate application of geophysical prospecting, in the modern sense, to oil-finding. As we all know, this is the fertile field in which the geophysical prospecting science and art has flourished and grown to its present stature of world-wide industrial importance.

It is of interest to point out that the idea of applying geophysical measurements in the search for oil could hardly have occurred much sooner because, according to DeGolyer,[2] the year 1913, only two years earlier, marks the beginning of the acceptance of geology as a guide to prospecting.

All of us realize how vast is our present profession. Few realize how quickly, in how very few years, it has developed.

The history of the development of geophysical exploration is very intimately related to the history of the Society of Exploration Geophysicists. Seismic and gravity crews were brought from Europe to the Gulf Coast in the early 1920's to aid in the search for salt dome oil fields. The spectacular success of these early geophysical surveys is well documented in published articles, textbooks, and technical monographs. But, the first flush of success faltered. It became necessary for two, heretofore almost unrelated, scientific disciplines, geology and physics, to merge their thinking in order to work together for further progress. And so it came about, in 1930, that a group of geologists and geophysicists, who recognized the close interdependence of their problems and the need for the interchange of ideas, formed an organization for the express purpose of developing and improving geophysical techniques in the search for oil. Appropriately enough, the first meetings were held in Houston, Texas, the center of geophysical activity at the time.

The name chosen for the organization was *The Society of Economic Geophysicists*. The list of charter members includes 46 names, among them such well-known geologists as Alexander Deussen and Donald C. Barton. Today the membership approaches 3,000 in 41 states and 49 foreign countries. There are nine local sections and three student sections. Four additional sections are in process of formation and affiliation in the United States and abroad. The Society's magazine *Geophysics* has world-wide circulation.

The scope of professional interest embraces all problems related to the scientific exploration for mineral resources of all kinds in the earth's crust. This broad scope was clearly envisioned by the founders of the Society as indicated by its first name. However, for reasons which are not now apparent, the name was changed a year later to *The Society of Petroleum Geophysicists*. Five years later, realizing that the limitation in scope implied by this name was undesirable,

[1] E. A. Eckhardt, "A Brief History of the Gravity Method of Prospecting for Oil," *Geophysics*, Vol. 5 (July, 1940).

[2] E. DeGolyer, "The Development of the Art of Prospecting," Cyrus Fogg Bracket Lecture, Princeton University, 1940.

the present name was chosen: *The Society of Exploration Geophysicists.* With this name, we have now lived 15 years and have fond hopes of living happily forever after.

The Society of Exploration Geophysicists is affiliated with the American Association of Petroleum Geologists, under whose motherly wings it nestled in the first few years of its existence. It is also a member society of the American Geological Institute.

So much for history. Let us now consider the present economic stature of geophysical exploration. The Society of Exploration Geophysicists is professionally concerned with all geological exploration problems: petroleum, mining, civil engineering, and so on. The applications to exploration for petroleum are well developed. Last year, official SEG records show, $325,000,000 was invested in world-wide geophysical explorations by the oil industry alone. This represents a phenomenal increase over 1950 of $100,000,000 or nearly 50 percent. Additional millions were undoubtedly spent in mining explorations and for research in the improvement of present techniques and the development of new methods. The increased expenditures last year are due partly to inflationary rise in costs and partly to increased activity. When we realize the magnitude of our present operations, we must concede that we are no longer in the geophysical *game.* We are in the geophysical *business.*

Geophysical exploration activity today,[3] on a world-wide scale, marks an all-time high: 791 seismic crews, an increase of more than 20 percent over 1950; 123 gravity crews, an increase of 12 percent over 1950. Surprisingly, the trend of geophysical activity last year was toward the United States, away from foreign areas. This probably reflects industrial concern over unstable political philosophies about mineral resources.

The mineral industries and the petroleum industry in particular are investing great sums of money in geophysical exploration. The commercial acceptance of geophysics is justified by its success. Lahee's well-known and exceedingly useful statistical analyses[4] report the success expectancy of a wildcat well drilled in the hope of discovering a new old field (a "new-field wildcat" in Dr. Lahee's terminology) for various bases of selecting the drilling site. Rounding out the small annual fluctuations (which are not significant for our purpose), we get averages for the last five years (1947–1951) in the United States as follows:

Basis	*Success Ratio*
Non-Technical (random drilling)	1 in 30
Geological	1 in 10
Geophysical	1 in 6
Combined Geological and Geophysical[5]	1 in 5

[3] E. A. Eckhardt, "Geophysical Activity in 1951," Official Committee Report to Society of Exploration Geophysicists, Los Angeles, California, March 24, 1952.

[4] F. H. Lahee, "Exploratory Drilling in 1950," *Bulletin of the AAPG,* Vol. 35 (June, 1951).

[5] This is a separate classification in Dr. Lahee's statistics and not the combination of the separate geological and geophysical classifications.

The improvement resulting from the application of the best modern exploration technique—geology and geophysics combined— is very impressive. Compared to random drilling, the saving amounts to 25 dry holes per discovery, 4 dry holes instead of a wasteful 29. When we consider that the total expenditure for the geophysical data is only about 10 percent of the total cost of oil exploration, these statistics take on additional significance.

And still, Dr. Lahee's tables continue to show, year after year, a surprisingly large number of wildcats in the non-technical column! It is encouraging to see, however, that the number is gradually decreasing. Here, indeed, is a fertile field for our public relations committees.

Modern geophysical instruments and techniques are well developed, especially in the United States and Canada. Qualified geophysicists throughout the world concede freely that American instruments and American geophysicists are the best to be had. The technical achievements are indeed impressive. Let us consider one example. Twenty odd years ago, the establishment of a single gravity station required two full days with a large truck load of equipment, and the result, which did not become available until the pendulum could be standardized at the home base several months later, had a probable error of plus or minus two or three milligals. Today, only two short decades later, a modern gravimeter about the size of a two-quart Mason jar and weighing only six pounds will establish a gravity station in about two minutes with an accuracy of plus or minus 0.03 milligal. This represents a fifty-fold advantage in weight, a one hundred-fold gain in accuracy, and a five hundred-fold gain in speed. Similar examples could be cited with other geophysical instruments. Without these technological improvements, geophysical prospecting as we know it today would be entirely ineffectual and prohibitively expensive.

An asset of even greater importance is our stock of trained geophysical manpower which has been painstakingly assembled and carefully nurtured over the years. The solution of complex geological exploration problems, even with the best geological and geophysical data obtainable, depends essentially, in the final analysis, upon the interpreter's personal experience and judgment. The present and prospective shortage of technical talent in our schools and colleges presents a challenge which we must meet.

Let us now peer into the future. We are often reminded that our present proved petroleum reserves are only sufficient to supply the wheels of industry for about fifteen years and, therefore, that we have an urgent need, in the face of rising demand, to increase the discovery effectiveness of our exploration techniques. That is a real problem which faces us right now—today. Many geophysicists and geologists are devoting their best efforts, generously supported by management, toward the solution of this problem. I am quite confident that so long as any oil remains in the earth to be discovered profitably it will be found.

We are not doing too badly right now. Last year, according to published statistics, the United States produced 2,243,000,000 barrels of crude oil. That is

a lot of oil—an all-time record. It takes a lot of doing to discover enough new oil to supply the demand. However, the exploration departments of the American oil industry did even better. The estimated amount of reserves in the new oil discoveries during 1951 not only replaced the amount consumed but also added about 1½ billion barrels to the "proved reserves."[6]

On the other hand, young men entering college are often deterred from choosing geophysics or petroleum geology as a career because they have heard the prophets of doom shouting about the impending shortage of oil. Unfortunately, it is the brightest young men, the men who could be expected to contribute most to the solution of the problem, who give heed to these dire predictions and are misled into other fields of endeavor.

Therefore, it is worth while to take a broader view. The total amount of petroleum discovered throughout the world to date, including about 70 billion barrels consumed and 80 to 100 billion barrels in the "proved reserves," is about 150 billion barrels. Estimates of potential world petroleum resources which remain to be discovered are about 600 billion barrels[7] or four times as great.

At the present world-wide discovery rate of about 6 billion barrels of oil per year, this should keep us in the business for about 100 years.

Even this bright picture might be unduly pessimistic. It is based on the tacit assumption that oil is a one-crop proposition and that none is being formed in the earth today to provide distant future discoveries. Recent evidence suggests the attractive possibility that oil may, in fact, be forming in the vast volume of sediments being deposited today.[8] This opens possible glorious vistas for the future.

Of course, the possibility that this will influence your and my professional career is highly speculative. That is a subject which may well be the concern of other speakers on this platform in the years ahead. However, all predictions of our future oil supply have been notoriously short-sighted in the past. Perhaps I may be pardoned for leaning in the other direction to regain the balance.

As a professional society, the commodities the Society of Exploration Geophysicists has to offer the exploration industry are instruments, techniques, and ideas. Of the three, ideas are by far the most important. Paradoxically, ideas, while rare, are the cheapest ingredient of our industrial economy. The success or failure of a wildcat well costing perhaps as much as a million dollars is often crucially dependent upon the mental inspiration of the exploration geophysicists and geologists who selected the drilling site. It is the recognized responsibility of our societies and of meetings such as this to inspire all of us to

[6] Philip C. Ingalls, "Total Reserves Near 32 Billion Barrels," *Oil and Gas Journal*, Vol. 50, (January 28, 1952).

[7] Gail F. Moulton, "Is American Petroleum the Cause or Result of the Greatest Prosperity Known in History," *Petroleum Engineer*, Vol. 22, October, 1950.

[8] Paul V. Smith, Jr., "Preliminary Note on Origin of Petroleum," *Bulletin of the AAPG*, Vol. 36, February, 1952.

new and better ideas to improve our exploration techniques now and in the years ahead.

The president of a large oil company said recently:[9] "Science and technology are the biggest forces for progress in the oil industry today. Almost all of our present techniques and operating procedures are the results of improvements and developments made by scientists, engineers, and technologists. The conclusions of the technical men serve as a base for the decisions of management."

Surely, geophysical exploration for oil has reached maturity. Geophysical exploration for other minerals is on the way up. So long as we, geologists and geophysicists, continue to work together as we are now doing to develop new ideas to solve our problems as they arise, we as professional men can face the future with confidence.

[9] L. F. McCollum, "Petroleum Industry Benefits from the Application of Science and Technology," *The Mines Magazine*, Vol. 39, December, 1949.

GEOPHYSICAL ACTIVITY IN 1951*

E. A. ECKHARDT†

GEOPHYSICAL ACTIVITY IN THE OIL INDUSTRY

Unprecedented is the word which most aptly describes the expansion of geophysical activity which took place during 1951. The seismograph work done everywhere by the oil industry during the year required the full time services of 791 crews, an increase of 134 crews or 20.4 percent over 1950. Gravity work was also done in substantially greater volume during 1951, requiring the full time services of 123 crews, an increase of 13 or approximately 12.2 percent over 1950.

The number of crews reported as operating in the U.S. is plotted on a month-by-month basis for both seismograph and gravity in Figure 1. The chart covers a period of ten years and shows vividly that at no time during this period, and in fact during any other, did the number of seismograph parties rise at so rapid a rate. The increase in gravity operations was less pronounced, but strongly upward. The chart shows at the peak in November 600 seismograph parties working in the U.S. The slight drop in December is of no significance. Such drops have occurred at the same season in practically every year and are of a seasonal character. If during all of 1952 seismograph work were done at the year-end rate of 1951, without further increase, the 1952 rate would exceed the average 1951 rate by approximately 10 percent. Actually it is to be anticipated that the increase will be moderately greater than this.

In accomplishing the increase which occurred last year, the geophysicists have accomplished something of a miracle. Their number is not capable of expansion at will. A geophysicist is the product of training and experience. The acquisition of both takes time. The number of technically trained men that became available from the colleges and universities last year was far short of the demand for them by all industry, and the shortage had its full effect in limiting additions to the geophysical forces. The registration of the students now in the schools makes it clear that in the face of rising demand, the supply of graduates in the sciences and engineering will be decreasing for several years to come. The availability of suitably trained and experienced men is bound to prove a major obstacle in the maintenance and further expansion of geophysical services.

If you will take your hair down with me, you will admit that geophysicists,

* Report of the Committee on Geophysical Activity of the Society of Exploration Geophysicists. The members of this committee are A. A. Brant, Herbert Hoover, Jr., D. C. Skeels, and E. A. Eckhardt, Chairman. Presented at the Los Angeles meeting of the Society March 24, 1952. Manuscript received by the Editor March 24, 1952.

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on the average, are currently not doing the best possible job. That this is so is not particularly their fault. There just are not enough of them to handle the volume of work there is to do. Most of them have to keep track of more kittens than can be kept neatly tucked away in the basket. One must not be surprised if some of the kittens go astray.

While this is a familiar story to most of us who are directly engaged in

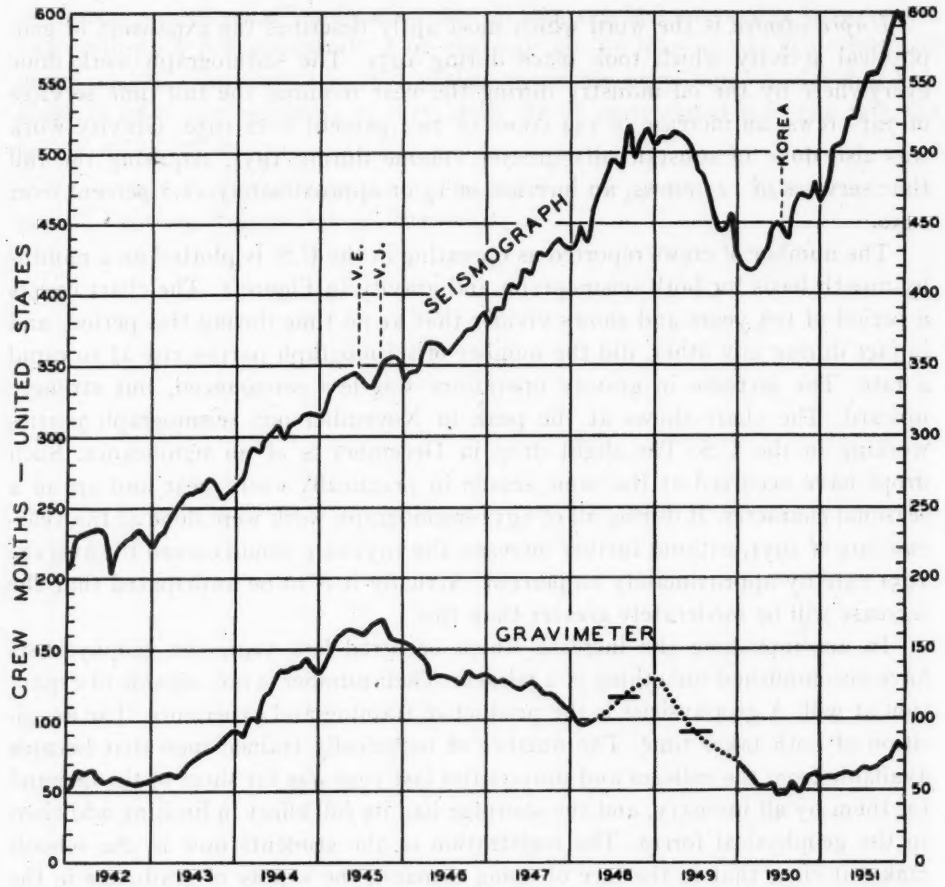

FIG. 1. Monthly variation in seismograph and gravimeter crew-months in the United States.

wrestling with these problems, there is need that it be fully understood also in other quarters. The intelligent expansion of geophysical services requires long range planning so that there is time to train men and give them the experience they will need to handle their jobs successfully. It is also important that each trained and experienced geophysicist be assigned in a manner to make the most effective use of his training and experience. There are not enough of them to go around; none of them should be wasted.

What has just been said about the manpower situation in our business when viewed against the background of our rearmament economy deserves the most careful consideration of our draft boards and the military authorities. Unless they, as well as industry, recognize that the pool of technically trained men is well below the needs of the country and temper their drafts from the pool accordingly, the vital defense effort will suffer. In the national interest they, too, have the obligation to make the best possible use of their technical training and experience when such men are called to active military service. Unless this obligation is recognized and made an integral part of selection policy, an already critical situation could easily become disastrous. It is reassuring to note that reasonable progress in this direction is being made. At best, however, the state of affairs can only be described as spotty.

Much has been heard in recent years from Gobble-de-gook Center about equality of sacrifice or the equal distribution of the burden. It is an idea to which all of us can readily agree in principle. From some of its propounders one gets the impression that this is of first importance, a requirement to which all others must be subordinate. In truth our greatest need is to win the struggle in which we are engaged. In sheer weight of manpower we are outnumbered, and we can hope to win only by superior use of our technology and technologists. Should we take technologists out of technology in order that equality of sacrifice may be more completely achieved? A complementary question is, "Should we permit anything that will make the winning of the struggle more uncertain, lengthen its duration and increase its cost?" An intelligent answer to the second question automatically provides an answer to the first. This answer may not be socially palatable, but we had better heed it and thereby improve the chances of saving our skins.

The question of geophysical personnel has been dealt with at such length because it is critical in determining whether the need for geophysical service by the oil industry can be met in quality and quantity. We need more well-trained and experienced men for the operations in being. We will need still more if we are to expand the operations to meet the apparent demand.

North America contributed the major component to the 20.4 percent increase in the world total of seismograph operations during 1951, the actual increase being 1,519 crew-months for a 1951 total of 8,248. For Canada the increase was 286 and for Mexico 90. Percentage-wise the increase was greatest for Mexico (66.7 percent). Canada was next with an increase of 23.9 percent and that for the U.S. was 21.8 percent or somewhat, but not markedly, above the average world increase. The trend away from the U.S. noted in the report for 1950 was clearly reversed last year. There was a less than average increase in the Eastern Hemisphere and a small decrease in volume in South America. The greatest percentage increase occurred in Africa, where activity more than doubled, and the greatest decrease, both numerically and in percent, took place in the Far East. This decrease is probably closely related to the unsettled political situation in that area.

The world distribution of seismograph operations in 1951 is shown in Figure 2. The pie is larger than for the preceding year but no major change in the size of the slices is apparent. Here and in the other charts the plus and minus signs indicate whether any given slice is larger or smaller compared to 1950.

In the U.S. the 1951 increase in seismograph operations amounted to 1,172

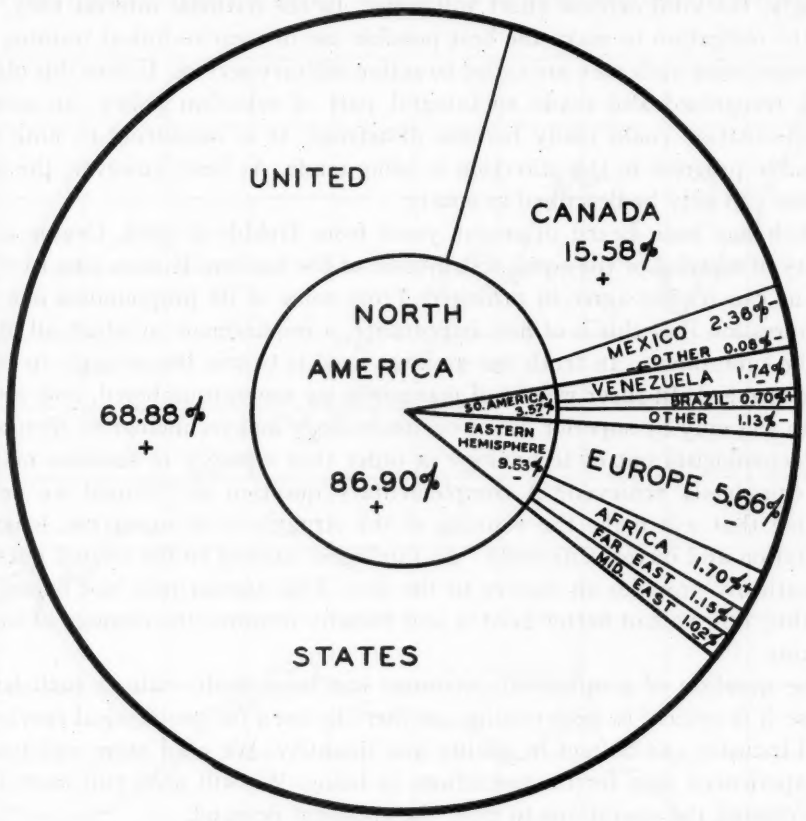

FIG. 2. World distribution of seismograph operations in 1951.

crew-months. The Rocky Mountain States, Louisiana, and Texas accounted for nearly all of it, and in the order named, the increases being 570, 303, and 241 crew-months and 46, 41, and 10 percent, respectively. The geographic distribution of seismograph operations in the U.S. in 1951 is shown in Figure 3. Texas retains its commanding lead, but by a reduced margin. As will be noted, Texas, the Rocky Mountain States and Louisiana accounted for approximately 83 percent of the seismograph work done in the U.S. last year. Among the Rocky Mountain States activity was most concentrated in New Mexico, Wyoming, Colorado, and Montana, in that order, and these states were the seat of over 75 percent of the activity of this area.

Gravity operations the world over rose moderately during 1951 from a level of 1,320 crew-months in 1950 to a total of 1,481. As will be seen by reference to Figure 4, over half of such work last year was done in the U.S., which accounted for practically the entire world increase. The downward trend in evidence in U.S. operations for several years back was definitely reversed and at year end they were substantially at the highest level of the year. In Canada gravity work

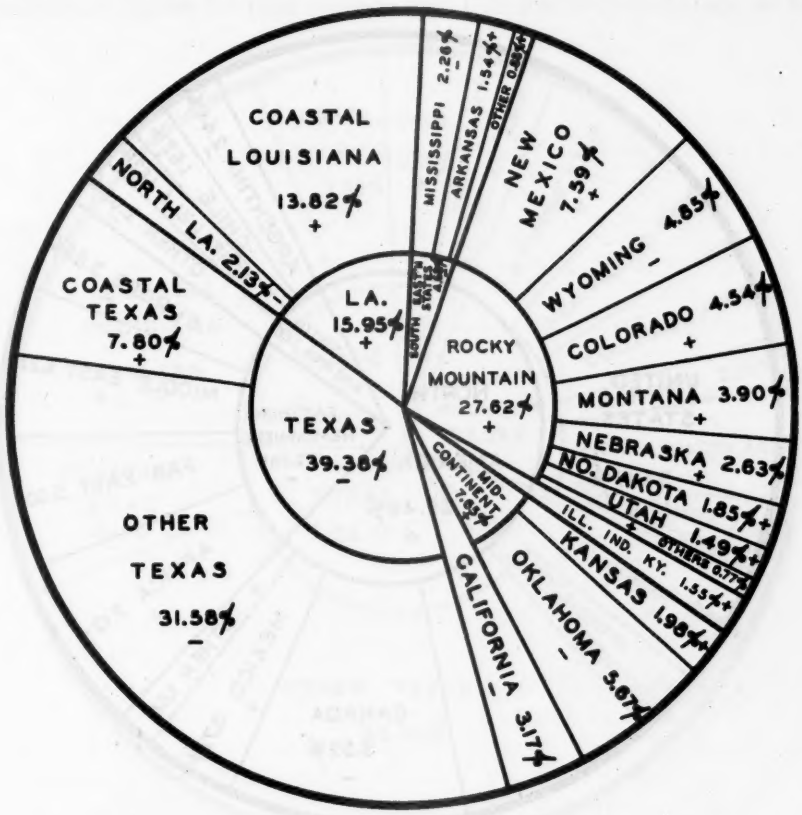

FIG. 3. Distribution of 1951 seismograph operations in the United States.

was done in practically the same volume as the year before and therefore its contribution to the world total declined. Considerable gravity work was done in Mexico last year, and it more than doubled its percentage share of the world effort. As was true also in seismograph operations, the greatest decline in gravity work was experienced in the Far East. Other shifts are readily apparent from the chart.

The geographic distribution of gravity operations in the U.S. in 1951 is shown graphically in Figure 5. Out of a total of 802 crew-months reported for the country, Texas, with 36.7 percent, continued to hold the No. 1 spot. There

was a relatively pronounced gain in Louisiana to a level about equal to that of the Rocky Mountain States. Between them these three areas accounted for over 84 percent of domestic gravity operations last year. The greatest gain occurred in Louisiana, more particularly in coastal Louisiana, and the greatest relative loss was recorded for Mississippi.

Again it is impossible to make a report on magnetometer operations on a

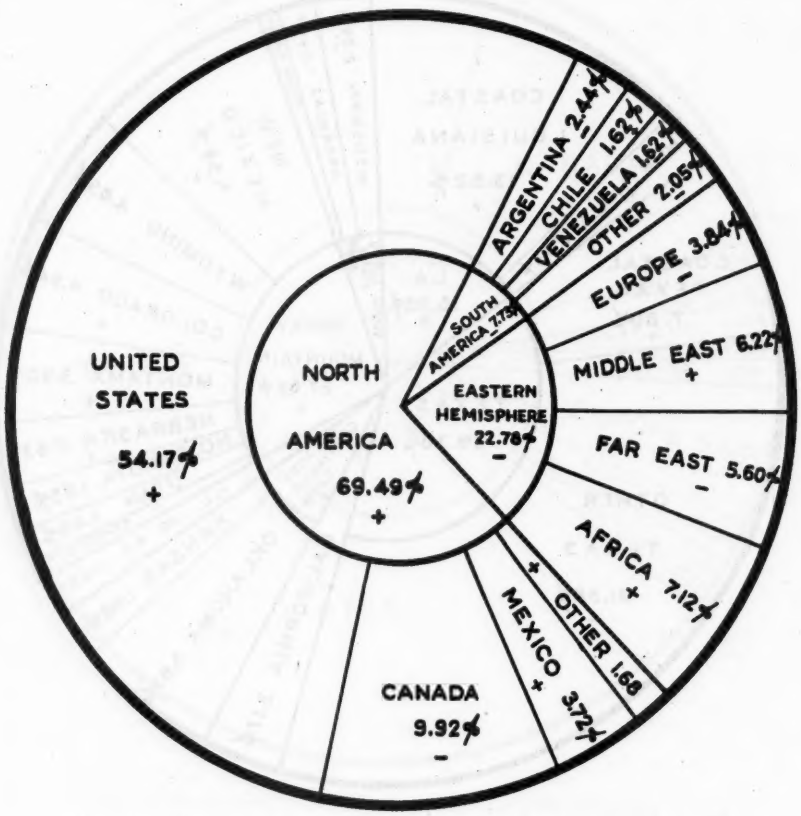

FIG. 4. World distribution of gravimeter operations in 1951.

basis comparable with the other activities. Data received do not differentiate between ground party and aeromagnetic crew-months, and since ground parties may use a variable number of instruments, the meaning of ground crew-months is correspondingly indefinite. Since aeromagnetic and ground parties involve cost ratios of the order of 10 to 1 and data production in ratios of the order of 100 to 1, the problem of keeping track of even trends becomes somewhat complicated. To date your committee has had no success in providing you good data for magnetometer operations. It is probably true, however, that much more

magnetometer work was done by and for the oil industry last year in comparison to those immediately preceding.

For its geophysical operations in 1951. the oil industry probably spent not less than $300,000,000 and possibly as much as $350,000,000. The bill for 1951 is greater in part because of substantially greater volume and in appreciable part because of greater unit costs.

Preliminary figures for 1951 indicate that U.S. production of crude oil for the

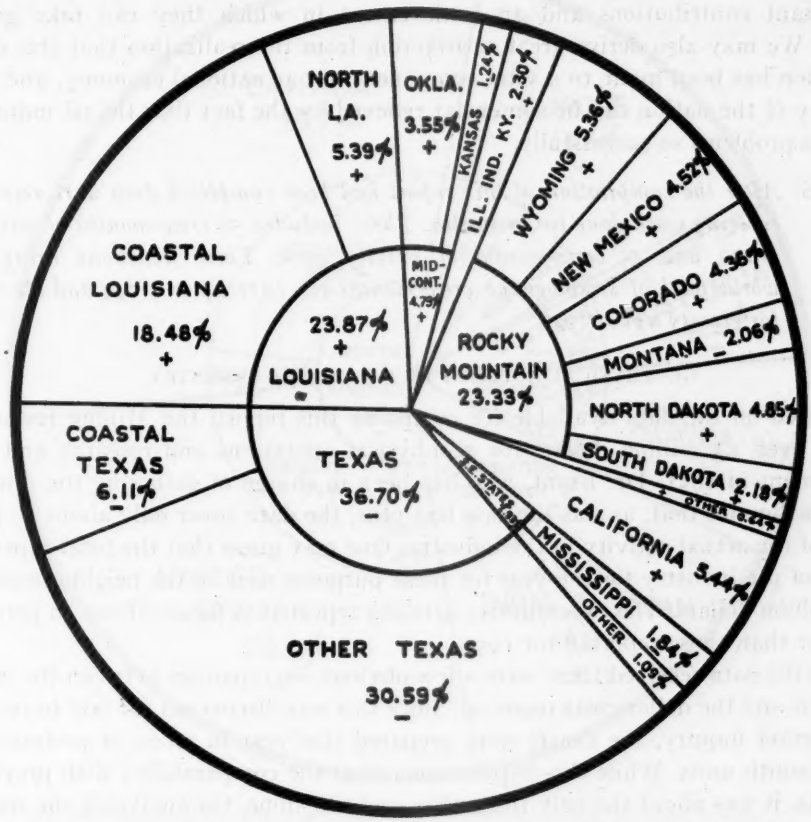

FIG. 5. Distribution of 1951 gravimeter operations in the United States.

year reached an all-time high of 2,242,698,000 barrels, exceeding the previous peak of 1948 by 10.6 percent. As a result of 1951 operations there was a net increase of 1,416,000,000 barrels in the estimated crude oil reserves of the country. The oil produced during the year was replaced by new discoveries and an increment of roughly 1.4 billion barrels was added to reserves. The discoveries for the year therefore were 3.659 billion barrels approximately. Before 1951 the peak year was 1937. The following comparisons for the two years are of interest, the units being millions of barrels:

	1937	1951
Total Discoveries	3,342	3,629
Production	2,042	2,213
Net Addition to Reserves	1,300	1,416

It is clear that 1951 was an all-time record year for the U.S. oil industry with respect to total discoveries, production, and net addition to reserves. In fact, it appears to have been a record year for the industry in all respects with the notable exception of profits. It is a record to which geophysicists have made important contributions and an achievement in which they can take great pride. We may also derive great satisfaction from the realization that this contribution has been made to a vital component of our national economy, and the anxiety of the nation can be somewhat relieved by the fact that the oil industry met its problems so successfully.

P.S. *After the compilation of this report had been completed data were received covering work done in Australia. These included 58 crew-months of seismograph and 45 crew-months of gravity work. These additions bring the world total of seismograph crew-months for 1951 up to 9,549 and the total for gravity up to 1,526.*

GEOPHYSICAL ACTIVITY IN THE MINING INDUSTRY

Based on the data available for compiling this report, the Mining Industry spent over 3.5 million dollars for geophysical operations and research and development in 1951. Dr. Brant, who has been in charge of gathering the mining data, estimates that, as was the case last year, the data cover only about 60 percent of the actual activity in the industry. One may guess that the total expenditures of the industry for the year for these purposes were in the neighborhood of six million dollars. The expenditures actually reported to us are about 50 percent greater than those reported for 1950.

In the data received there were a few obvious discrepancies between the man-months and the dollar costs reported. Since this was discovered too late to rectify by further inquiry, the charts were prepared this year in terms of professional man-month units. While this impairs somewhat the comparability with previous reports, it was about the only thing that could be done. On analyzing the result, one is tempted to conclude that this may prove to be a better one than the dollar basis used in previous years. One advantage is that distortions due to varying costs of similar work in various countries are avoided.

On this professional man-month basis, Figure 6 shows the geographic distribution of geophysical operations in mining for 1951. The seesaw relationship between Canada and the U.S. perceived in previous reports persists and in 1951 Canada took top rank in both man-months and dollars, with the U.S. in second place. The positions of Europe and Australia remain about the same. Out of Asia there are reports from only India and Japan, and these countries have expanded their activities relatively more than the others reported. In Africa the

volume of activity actually decreased as compared to 1950 and the slice of the 1951 pie chart for this area became correspondingly reduced.

The distribution of the 1951 work in mining geophysics between the methods used is shown in Figure 7 which is also on the professional man-month basis. Ground magnetics and research and development, at 22.4 percent and 22.3 percent, respectively, accounted for the largest sectors, although electrical meth-

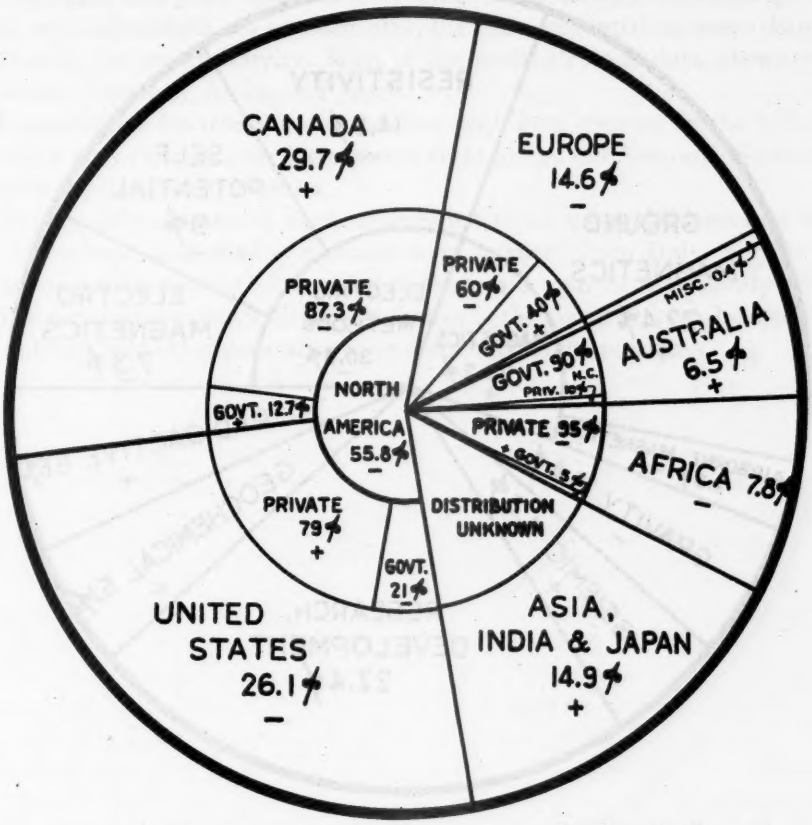

FIG. 6. World distribution of geophysical operations in mining, by areas, in 1951. Professional man-month basis.

ods as a group represented 30.8 percent of the total. These distributions would not be greatly changed on a dollar basis chart.

The situation is quite different, however, in the case of aeromagnetics. In the man-months chart aeromagnetics occupies a sector of 2.8 percent. In a dollar chart the sector would cover about 30 percent. This illustrates the difficulty of presenting a fair picture, a difficulty which is most pronounced in the case of aeromagnetics. Aeromagnetic surveys are usually paid for on the basis of money units per profile mile. It takes about one professional man-month to turn out a map

for about 500 profile miles. On the ground the same professional effort will turn out something in the neighborhood of 25 profile miles. In aeromagnetic surveying the professional man is about 20 times as productive as he is in ground surveys. He also spends money faster, as is usual in a mechanized activity. The over-all unit costs are greatly reduced, however. It by no means follows that ground mag-

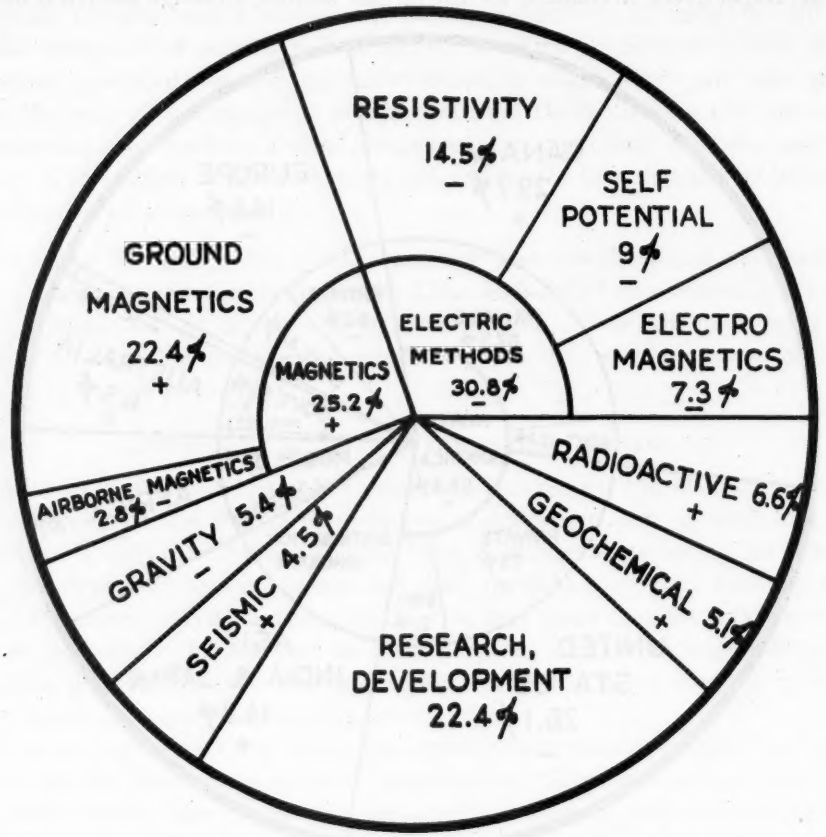

FIG. 7. World distribution of geophysical work in mining, by methods, in 1951. Professional man-month basis.

netic surveys are rendered obsolete by aeromagnetic techniques. Canada occupied the "No. 1 spot" in both ground and aeromagnetic activity last year.

Some things not apparent from the charts deserve mention. Aeromagnetic activity in 1951 was greatest in Canada, the volume in the U. S., Sweden, Finland, and Africa, as reported, being in that order. Canada led also in ground magnetics with such work in the U.S., Africa, India, Australia, and Sweden, being in decreasing order. Gravity work was done in about equal amounts in Canada and the U.S., with Australia, France, and Africa next in that order. In self-potential surveys, the U. S. ranked first, followed by Japan, Africa, India, and, Canada in

the order named. In resistivity work, the U.S. also held first place, followed by Africa, India, Canada, Japan, and Switzerland. In electromagnetic surveys, Canada was outstandingly first with the U.S., Sweden, and Finland tying for second place. In seismic surveys, Canada was also the leader, by a slight margin, with Switzerland and Japan being in second and third positions, respectively. Most of such work in Japan was related to coal. In radioactivity surveys, the U.S. occupied first place with a commanding lead. Australia was second, Canada third, and India fourth. In geochemistry, the U.S. accounted for more than three quarters of the world activity. Most of the remainder was done about equally in Canada, Australia, Africa, and Japan.

Expenditures for research and development were greatest in the U.S., with Canada a very close second. India was in third place, and Australia, Switzerland, and Africa followed in that order.

Twenty crew-months of work, distributed in an unspecified manner among gravity, seismic, and electric methods were reported from Italy. For these, 20 professional man-months were added to the world total in an arbitrary manner.

The committee extends its sincere thanks to the many people whose contributions of data and other assistance have made this report possible.

GEOPHYSICAL EXPLORATION IN WESTERN CANADA*

H. M. HOUGHTON†

This paper is restricted to a statistical study and to operational problems which are peculiar to the bush country of northwestern Alberta.

Figure 1 is a map showing most of the Dominion of Canada with the major oil fields of Redwater, Leduc, and Turner Valley indicated by name. The dotted line incloses the area in which active exploration is taking place. Note the completed pipe line running from Edmonton through Regina with a branch line to Winnipeg, continuing on to Superior, Wisconsin, located at the most westerly part of Lake Superior. This pipe line feeds a substantial tank farm during the winter and supplies a fleet of tank ships, operating on the Great Lakes, which carry the petroleum to the areas of dense population in the vicinity of Toronto and Montreal. Existing gas pipe lines are found running from Bow Island, Turner Valley, and Jumping Pound into Calgary and from the Viking-Kinsella Gas Field to Edmonton and Red Deer. A proposed gas pipe line, shown as a double line, will run from the area east of Calgary through Regina and Winnipeg past Fort William, Ontario and on east, still in the Dominion, to Toronto and Montreal. Other projected oil or gas pipe lines are indicated by dashes and run from Edmonton to Vancouver, B. C., and from Edmonton past Calgary and Pincher Creek across the border to Spokane and Seattle.

Figure 2 shows exploration by gravimeter and magnetometer during the period 1946 through 1951. The length of the bar in each case represents the number of crew months worked in each province. You will note that there has been no activity by either of these methods in the Province of British Columbia and only a very small amount in Manitoba. As might be expected, Alberta has had substantially more gravimetric and magnetic exploration than has the Province of Saskatchewan.

Figure 3 shows the seismic activity in Western Canada also expressed in terms of crew months. Seismic exploration in British Columbia did not start until 1948 and grew only slightly in 1949 with a decrease in 1950 and an increase to 15 crew months in the year of 1951. Note that the bar scale for seismic activity has been reduced by a factor of one to five as compared to the bar showing magnetic and gravimetric activity on the previous figure. Here again Alberta has had much the greatest amount of geophysical exploration. In 1946 there were 107 seismic crew months in the province, growing to 146 crew months in 1947 with a very sub-

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† Amerada Petroleum Corporation, Calgary, Alberta.

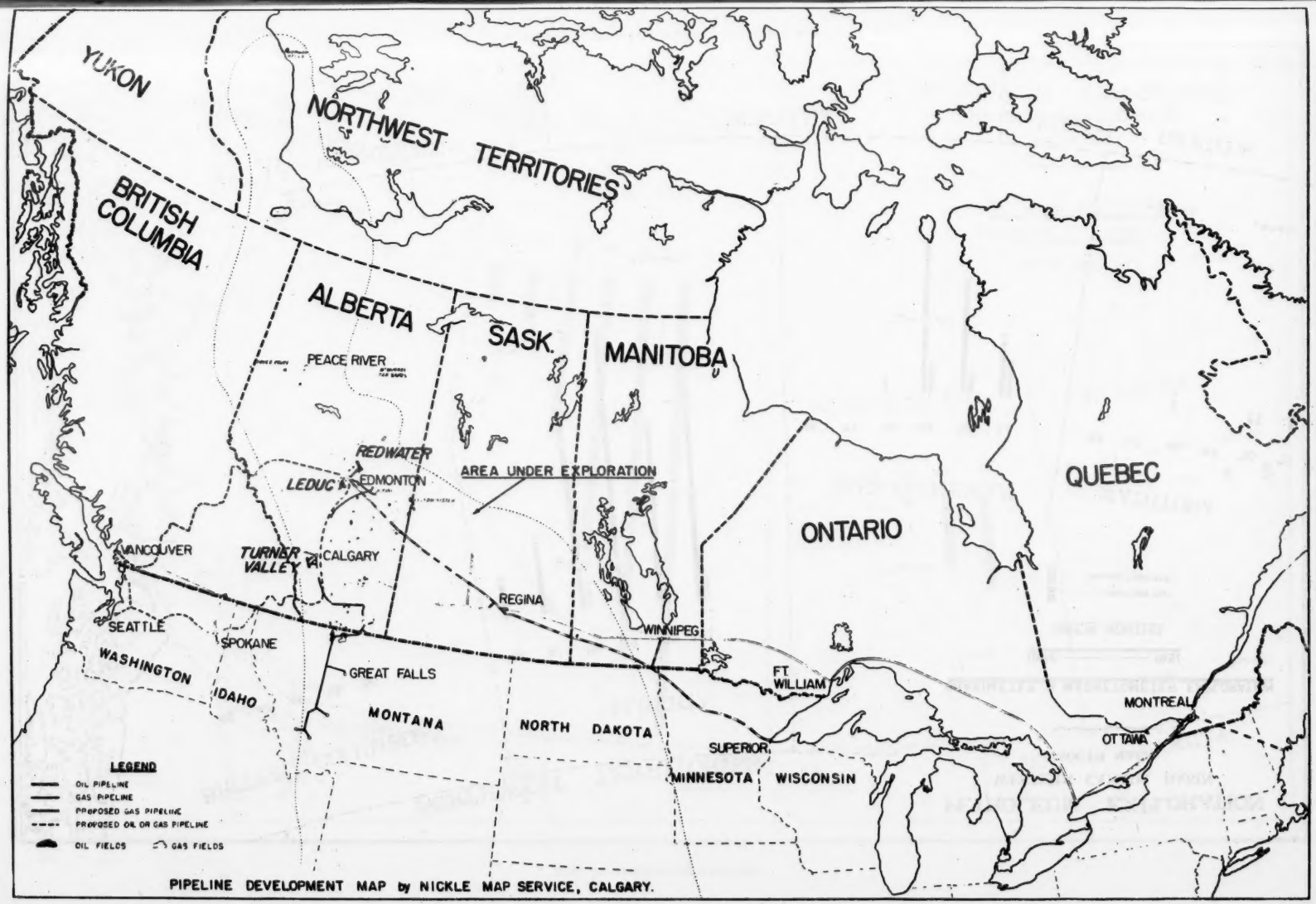


FIG. 1. Area of active exploration for oil and gas in Canada.

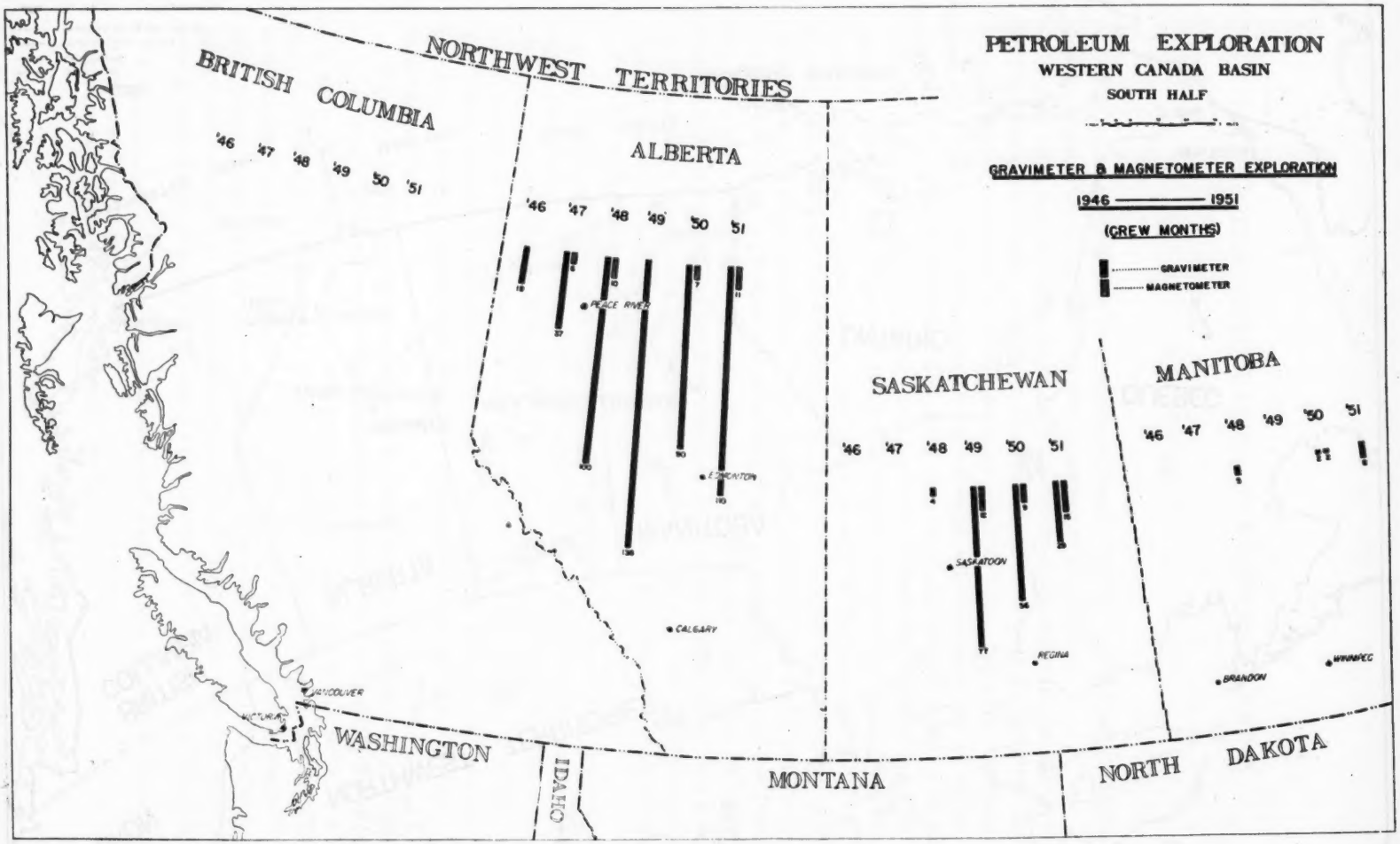


FIG. 2. Gravimeter and magnetometer exploration.

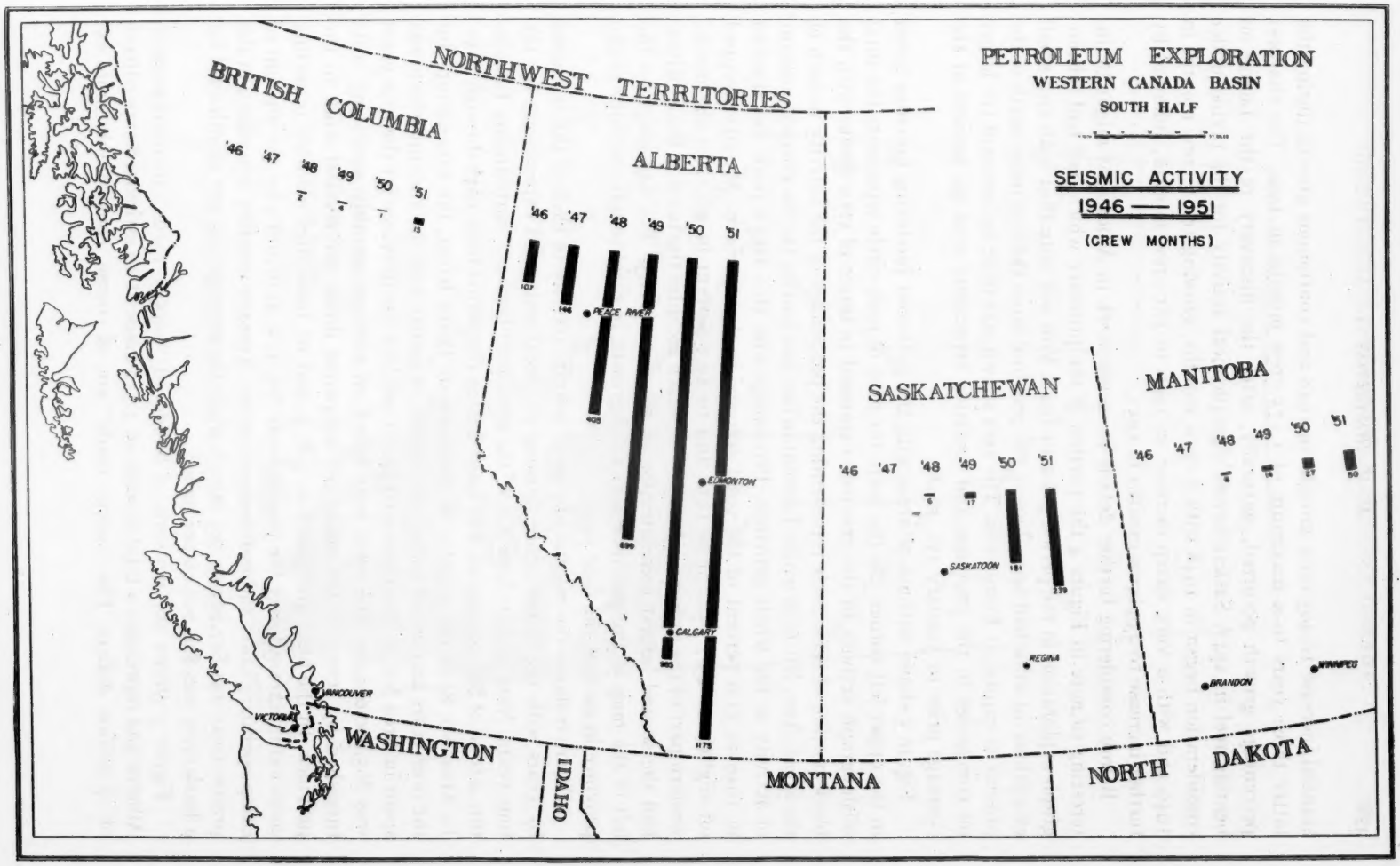


FIG. 3. Seismic exploration.

stantial increase to 405 crew months in 1948 and continuous growth during the latter three years to a maximum of 1,175 crew months in 1951. The sharpest percentage growth occurred, naturally, after the discovery of the Leduc oil bearing reef in 1947. Saskatchewan's geophysical activity for the period under consideration began in 1948 with 6 crew months, growing to 17 crew months in 1949 and with a very sharp increase in 1950 to 181 crew months, followed by further increase to 239 crew months in 1951.

Before considering further details in recent work in Alberta, it might be interesting to note in Figure 4 the portion of the province which had had seismograph exploration in the period prior to 1948. You will note that with two small exceptions no work had been done in the province more than 50 miles north of the provincial capital at Edmonton. The area shown was done by seven of the larger oil companies in the province and probably represents over 90 percent of the coverage prior to January 1st, 1948.

Figure 5 shows outlines of areas with the potential producing horizons listed in the upper left corner. On the map, the area of each circle represents the total seismograph activity in the province expressed in terms of crew weeks with the black portion of each circle representing the percentage of the activity in each of the areas. Area No. 6, in which Edmonton lies, has had by far the greatest amount of activity in the whole province. Percentage-wise this area's peak was reached in 1949 at 51.6 percent of the total activity in the province. Activity dropped off slightly to 45.7 percent in 1950 and to 45.3 percent in 1951. In the northwestern part of the province, Area No. 8, which includes the town of Peace River, had the second largest concentration of seismic activity. The bar graph to the left of the map of the province shows the growth in total seismic activity in the province in each of the four years.

Figure 6 shows the estimated cost of seismic activity in each of the ten areas by years with the larger figure showing the total estimated expenditure for the four years. Note that in Area No. 6, the so-called "fairway" surrounding Edmonton, a total of $26,100,000.00 was spent during the period from 1948 through 1951. In Area No. 8, in the vicinity of the town of Peace River, the expenditure for the four years amounted to $13,000,000.00, or nearly half the amount which was spent in Area No. 6. The estimated grand total for the province for the four years was $65,800,000.00. The costs were based on average monthly operating costs furnished by seven of the major oil companies doing geophysical work in the province. In the bush areas such as 5, 8, 9, and 10, individual monthly operating costs were increased over the prairie areas No. 1, 2, 4, 6, and 7 by the amount of camp operating costs and bulldozing expense. Average monthly costs used in the prairie areas was $17,000.00 per month while the average cost per month used for a bush crew was $29,000.00 per month.

Figure 7 shows the network of bulldozed "supply roads" in northwestern Alberta and represents a total mileage of 3,350 made at an estimated expenditure of 2½ million dollars. The "supply roads" are, of course, considerably more ex-

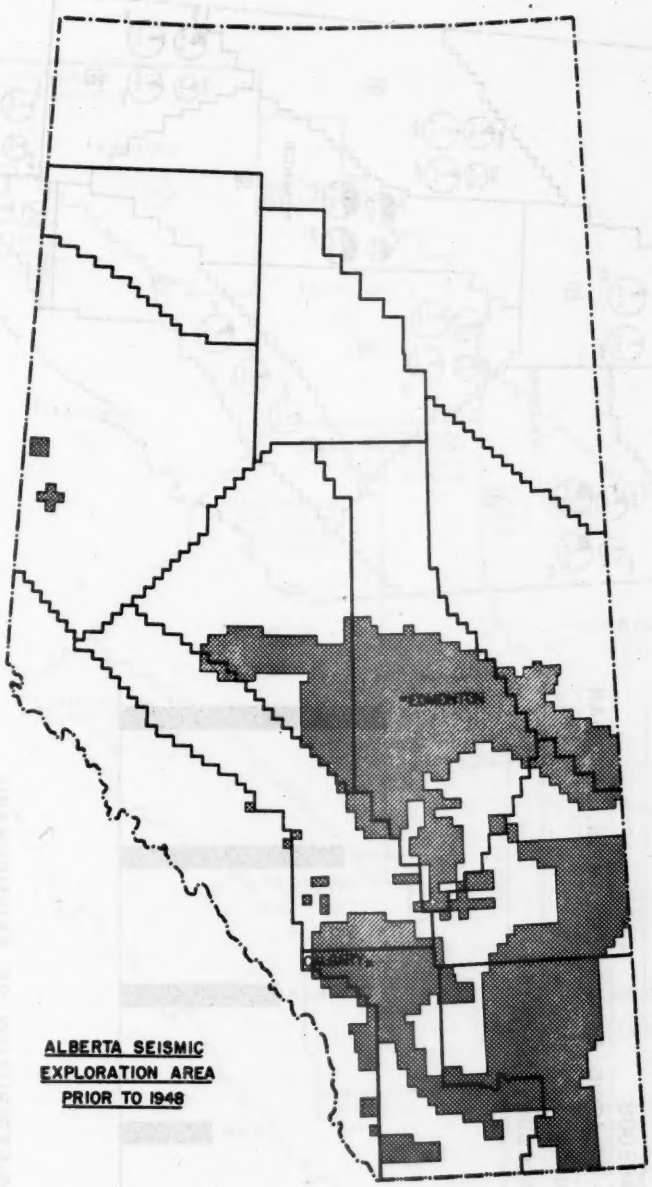
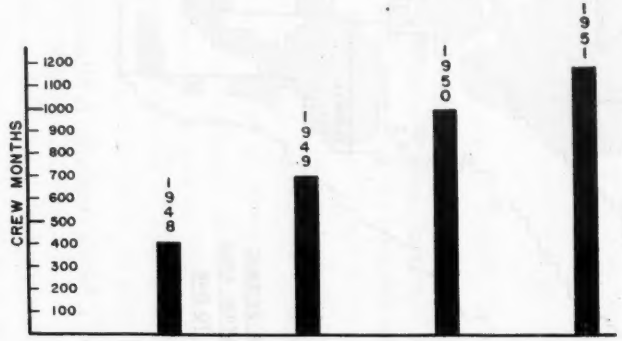


FIG. 4. Seismic exploration in Alberta prior to 1948.

AREA	POTENTIAL PRODUCING FORMATIONS
1	CRETACEOUS, JURRASSIC, MISSISSIPPIAN
2	CRETACEOUS
3	CRETACEOUS, MISSISSIPPIAN, DEVONIAN
4	CRETACEOUS
5	CRETACEOUS, MISSISSIPPIAN
6	CRETACEOUS, DEVONIAN
7	CRETACEOUS
8	CRET, TRIASSIC, PERMO-PENN, MISS., DEVONIAN
9	DEVONIAN
10	CRETACEOUS, DEVONIAN



DISTRIBUTION OF SEISMOGRAPH OPERATIONS IN ALBERTA 1948 —— 1951

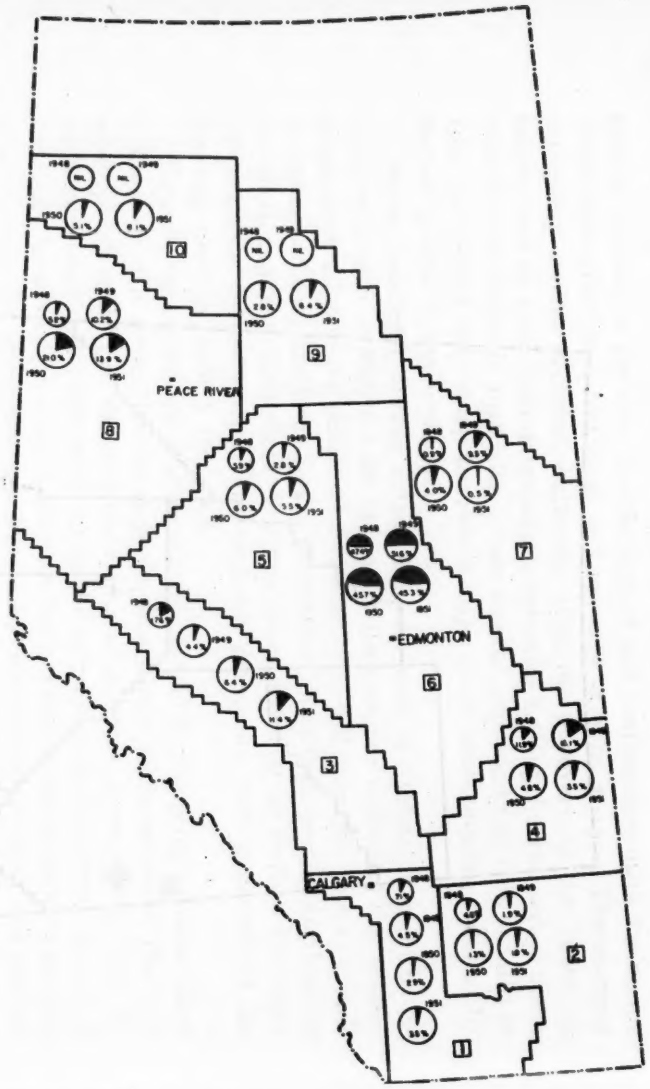


FIG. 5. Distribution of seismic operations in Alberta, 1948–51.

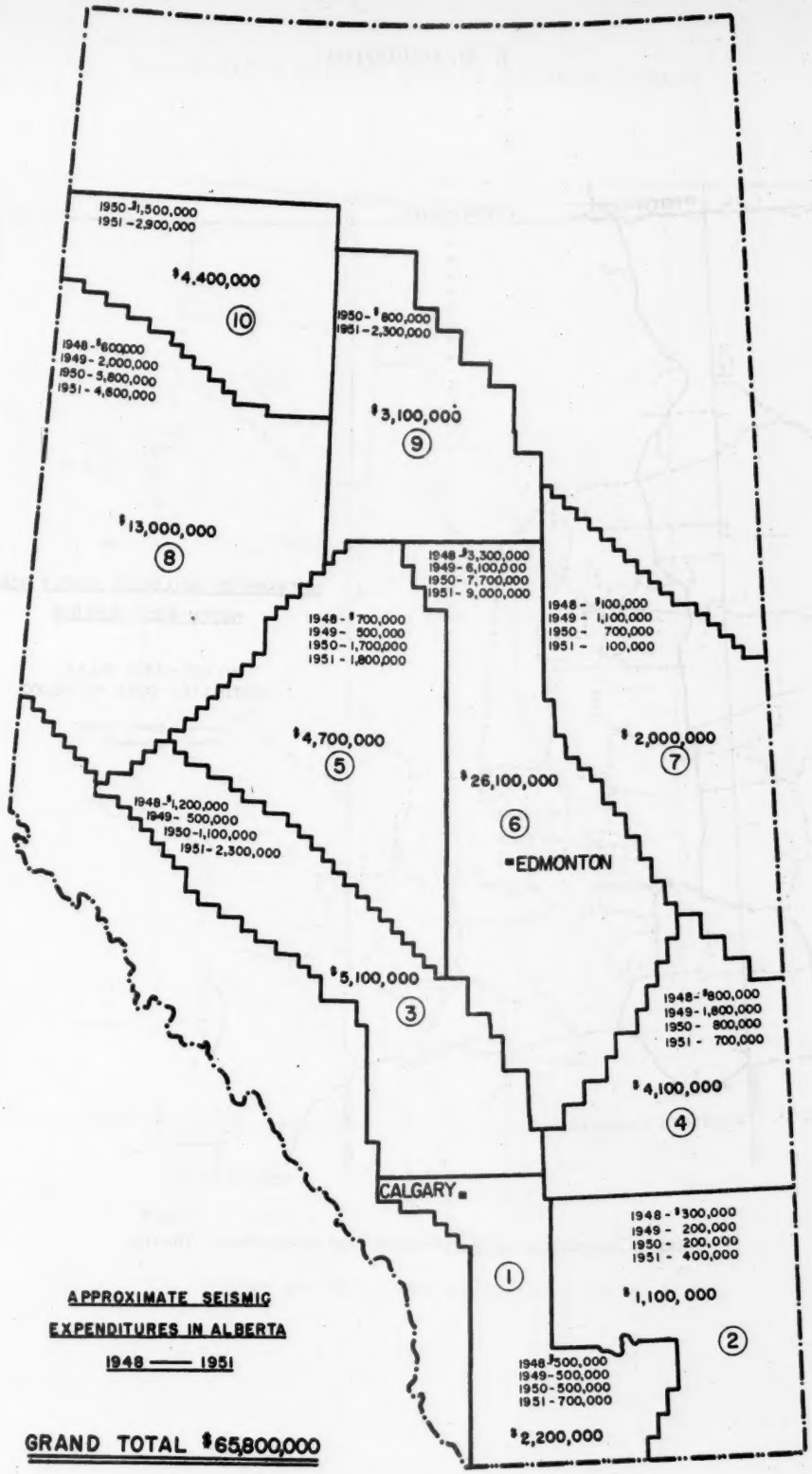


FIG. 6. Approximate seismic expenditures in Alberta, 1948–51.

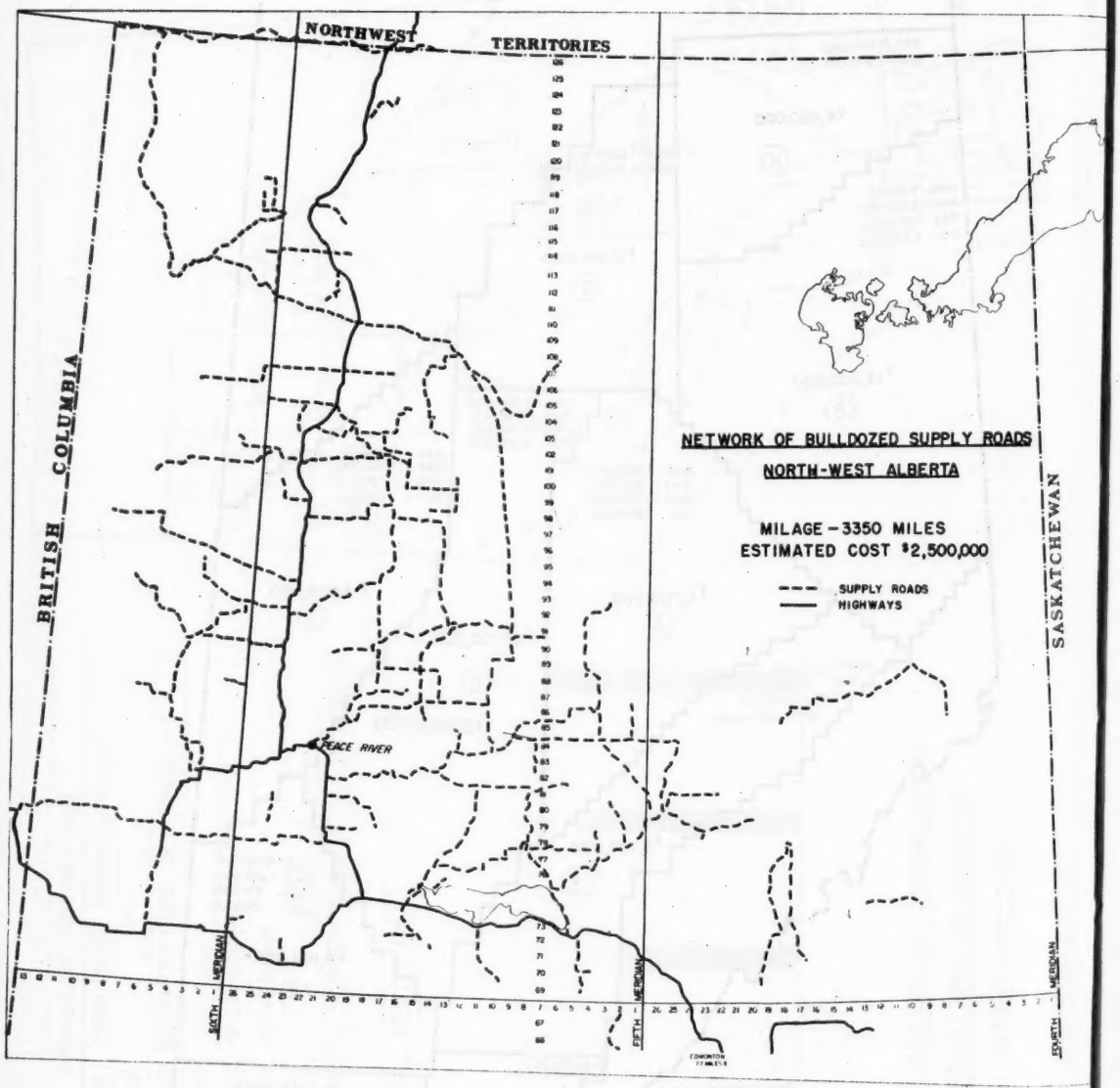


FIG. 7. Network of bulldozed supply roads in northwest Alberta.

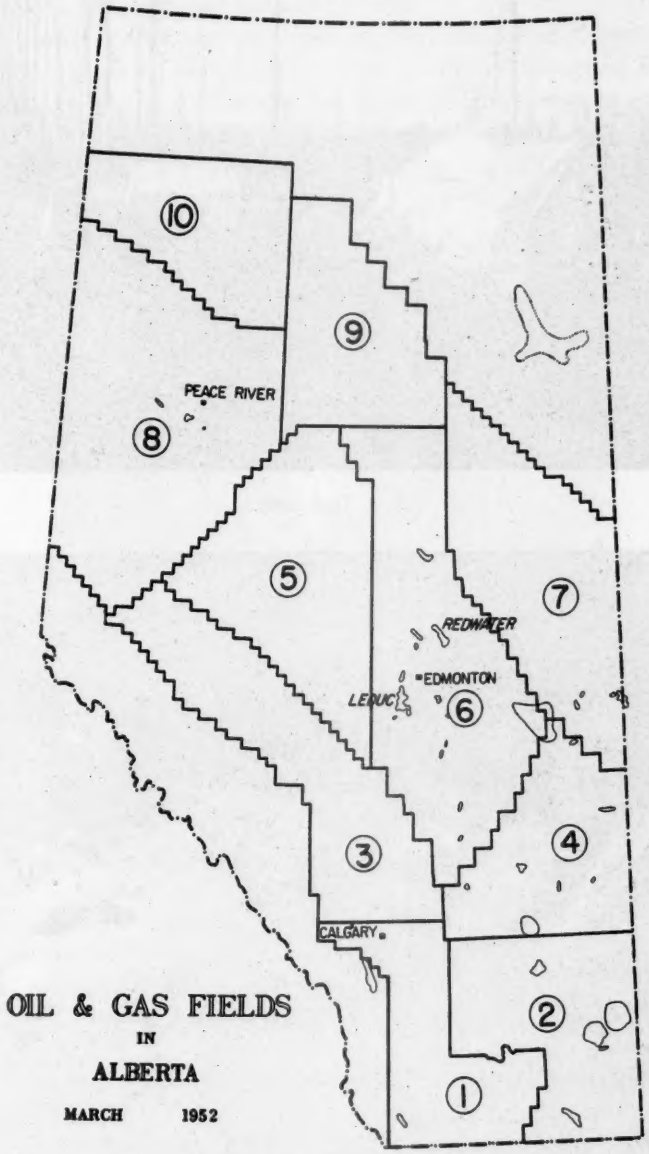


FIG. 8. Oil and gas fields of Alberta discovered to date.

FIG. 9. Tent camp.

FIG. 10. Aerial view of a major base camp.

pensive than the ordinary bulldozed trails which are used for seismic exploration. The cost of the supply roads was approximately $750.00 per mile. Seismograph bulldozed trails average in cost $300.00 per mile.

Figure 8 shows the oil and gas fields in the Province of Alberta which have been discovered to date. The dotted-in area to the northeast of Region No. 9 shows the location of the Athabaska Tar Sands which represents a very sizeable accumulation of hydrocarbons. In Area No. 6, northeast of the city of Edmonton, is the Redwater oil field and just southwest of the city is Leduc with the Wood-

FIG. 11. Supply road showing trailer unit being moved by truck.

bend field just to the north. South and somewhat west of the city of Calgary on the border of Area No. 1 is the old Turner Valley oil and gas field.

The remaining figures show operating conditions in some of the bush country in Alberta.

Figure 9 shows a tent "fly camp" which is moved very frequently to minimize the travel time of the men from camp to the scene of operations.

Figure 10 shows an aerial view of a major base camp located at Milepost 163 on the MacKenzie Highway, north of the town of Peace River. Note the plane in the foreground and a portion of the landing strip running diagonally toward the lower right.

Figure 11 is a view of a supply road, showing a trailer unit being moved by a truck.

Figure 12 shows a small Cletrac tractor down in the muskeg on the edge of the lake.

Appreciation is expressed to the following persons and companies for pictures, slides, maps and statistical information: The California Standard Company, The Canadian Gulf Oil Company, The Canadian Track Truck Limited, Century Geophysical Corporation, Delta Exploration Company, Geophysical Services Incorporated, the Geophysical Scout Check Committee of Alberta, Imperial Oil Limited, The Shell Oil Company, The Socony Vacuum Exploration Company, The Sun Oil Company, The Texaco Exploration Company (The Ohio Oil Company, particularly to Miss Doris Wagner and to Mr. E. H. Vallat who assisted with the accumulation of data and the preparation of the maps and other material), Mr. C. W. Bryant who made the slides, and my associates in Amerada—J. W. Clampitt, R. V. Mills, W. Parker, and W. E. Kelley.

FIG. 12. Cletrac sunk in muskeg pulling 250-gallon skid trailer.

EXPLORATION PROBLEMS OF THE WILLISTON BASIN*

K. E. BURG†

ABSTRACT

Discovery of oil in North Dakota by the Amerada Petroleum Corporation in their Clarence Iverson well in the vicinity of the Nesson Anticline, near the center of the Williston Basin, initiated a very active exploration program covering the entire basin. Interest in the area has continued because many of the wells drilled in other portions of the basin have resulted in discovery of oil in commercial quantities.

Because of the wide regional extent of the Williston Basin and presence of a rather complete Mesozoic and Paleozoic section, many exploration problems are encountered. The role of the seismograph in the solution of these problems is discussed.

INTRODUCTION

The Williston Basin, which is one of the oldest and largest geological basins in the North American Continent, has only recently received the active attention of the exploration departments of the oil industry. This acceleration of interest has resulted from the discovery of oil in the Devonian and in the Madison in the Amerada Petroleum Corporation Clarence Iverson well located on the large surface structure known in literature as the Nesson Anticline. Prior to this discovery a minor discovery was made in the northeastern flank of the basin near the town of Virden, Manitoba, where Madison production has been developed by The California Standard Company. Following the Amerada discovery, production has been obtained from the Madison and Devonian at several locations in Montana and in the Lower Cretaceous in Saskatchewan to the northwest. As a result of these discoveries, a very active leasing and geophysical campaign was initiated to the extent that a very large portion of the basin is under lease or reservation and more than 120 geophysical crews are now engaged in the area.

The purpose of this paper is to discuss briefly the generally accepted geology of the Williston Basin and to present some of the exploration problems encountered. The role of geophysics in helping to solve these problems will be outlined.

GEOLOGY OF THE WILLISTON BASIN

The Williston Basin covers an extensive area in the states of North Dakota, South Dakota, and Eastern Montana. It extends northward into the Western Canadian provinces of Manitoba, Saskatchewan, and perhaps into Eastern Alberta. The basin is named after the town of Williston, located in the northwestern part of North Dakota, because that town is near the center of the Cretaceous portion of the basin as outlined by contours on the Dakota Sandstone. See Figure

* Presented before the Midwestern Meeting of the Society November 20, 1951, Dallas, Texas. Manuscript received by the editor May 3, 1952.

† Geophysical Service Inc., Dallas, Texas.

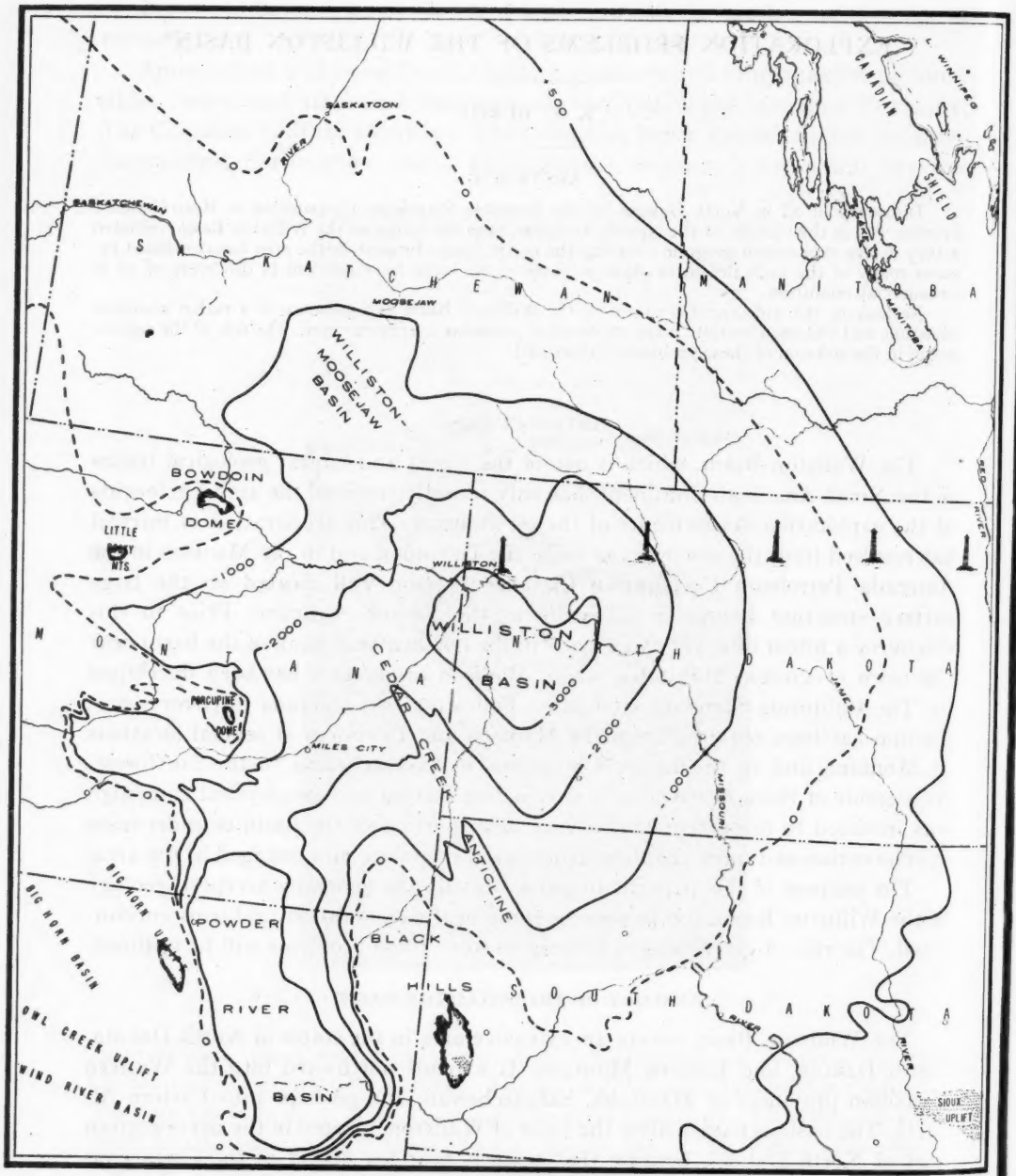


FIG. 1. Map shows relation of Williston Basin to the Rocky Mountain Shelf area and the Canadian Shield.

1. These contours are obtained in part from the tectonic maps of the United States and of Canada.[1,2]

Information obtained from many exploratory wells drilled in the last several years indicates that the Williston Basin, as outlined by the deeper Paleozoic formations, is much larger than originally believed. Inasmuch as these Paleozoic formations hold the greatest interest from an exploration and development viewpoint, this paper will deal with the problems encountered in this expanded area. In its broader aspects, the basin is bounded by the granites in the Sioux Uplift in Southeastern South Dakota, by the Pre-Cambrian Canadian Shield in Saskatchewan and Manitoba and the extension of the shield into Minnesota. To the northwest in Saskatchewan the Williston Basin merges into the Moose Jaw Syncline, and it appears that the deepest portion of the basin in Early Paleozoic time may be a considerable distance northwest of the center of the Mesozoic Basin. The Williston Basin is separated from the Rocky Mountain tectonic features by the massive Black Hills Uplift to the southwest and by the minor Porcupine Dome, the Bowdoin Dome, and the Sweetgrass Arch in Central Montana.

Dr. Wilson M. Laird[3] says that the Williston Basin is simply a basin on a large shelf east of the Rockies and west of the Pre-Cambrian Shield area in Canada and Minnesota and that it is one of several basins in the central part of the North American Continent that has been downsinking during most of Post Pre-Cambrian time. The relationships between this downsinking and that of the Central Montana trough, the Wyoming shelf areas and the Moose Jaw Syncline have been adequately described in the paleotectonic studies reported by A. J. Eardley,[4] L. L. Sloss,[5] John M. Andrichuk,[6] J. B. Webb,[7] and others. This study indicates that the basin has migrated considerably during the various periods of Paleozoic sedimentation, so that the areas of maximum thickness of each formation do not coincide.

The generalized west-east section through the northern portion of North Dakota, Figure 2, shows the presence of Tertiary beds, a rather full section of

[1] Tectonic Map of the United States, published by the American Association of Petroleum Geologists, 1944.

[2] Tectonic Map of Canada, prepared by the Geological Association of Canada, 1950.

[3] Wilson M. Laird, State Geologist, North Dakota Geological Survey, "Geology of the Williston Basin in North Dakota," *World Petroleum* (January 1952), pp. 42–49, and "The Williston Basin," *Oil in Canada* (March 17, 1952), 18–30.

[4] A. J. Eardley, "Paleotectonic and Paleogeologic Maps of Central and Western North America," *Bulletin of American Association of Petroleum Geologists*, Vol. 33, No. 5 (May 1949), 655–682.

[5] L. L. Sloss, "Paleozoic Sedimentation in Montana Area," *Bulletin of American Association of Petroleum Geologists*, Vol. 34, No. 3 (March 1950), 423–451.

[6] John M. Andrichuk, "Regional Stratigraphic Analysis of Devonian System in Wyoming, Montana, Southern Saskatchewan and Alberta," *Bulletin of American Association of Petroleum Geologists*, Vol. 35, No. 11 (Nov. 1951), 2368–2407.

[7] J. B. Webb, "Geological History of Plains of Western Canada," *Bulletin of American Association of Petroleum Geologists*, Vol. 35, No. 11 (Nov. 1951), 2291–2315.

Upper Cretaceous, a thin section of Lower Cretaceous and an interesting sequence of Jurassic and Triassic formations having the familiar names of Morrison, Ellis-Sundance, and Spearfish. The Paleozoic system includes an undefined sequence of Permo-Pennsylvanian beds and formations of Mississippian, Devonian, Silurian, Ordovician, and Cambrian age.

The major unconformity between Mesozoic and Paleozoic formations will no doubt play a very important part in the accumulation of oil in the Williston Basin because, as shown in part on the generalized cross-section, every Paleozoic

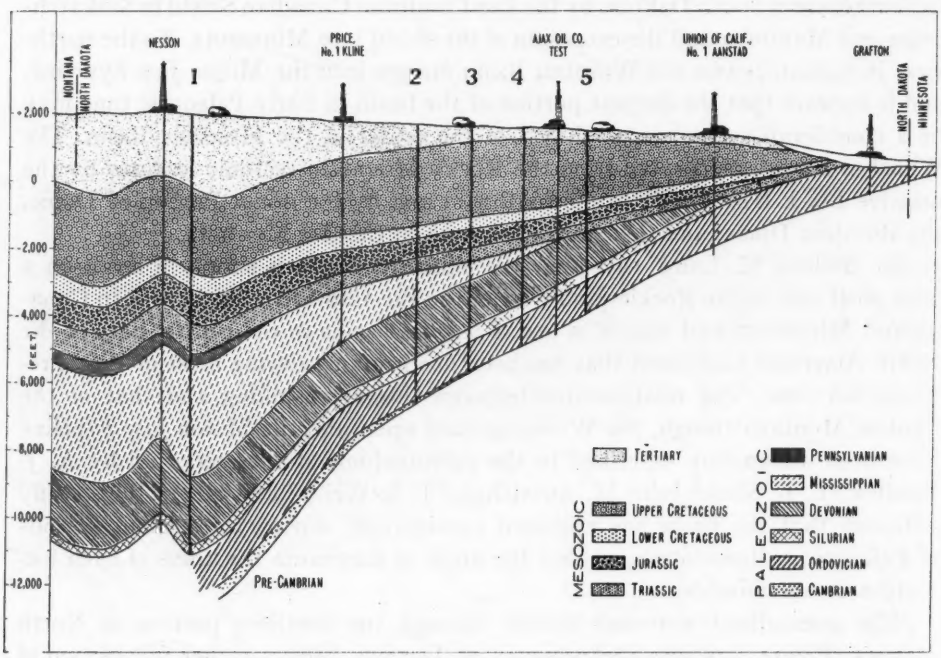


FIG. 2. Generalized west-east cross section through northern portion of North Dakota showing major unconformity between Mesozoic and Paleozoic.

formation was progressively exposed to erosion in the old Paleozoic surface. In North Dakota the Triassic is the basal formation of the Mesozoic, and it rests unconformably on all the Paleozoic formations from the Permian through the Silurian. The Ordovician and Cambrian are exposed in the eastern North Dakota flank of the basin.

As would perhaps be expected, other generalized cross-sections radiating outward into the other flanks of the basin show a different situation; for example, a section running southeastward to the Sioux Uplift shows all the Paleozoic beds disappearing suddenly against that uplift while still covered by a thick sequence of Mesozoic formations. A section running generally northward through the center of Saskatchewan would show that the Triassic, Jurassic, and Lower Cretaceous formations gradually disappear as the edge of the Canadian Shield

is approached, whereas the Devonian and Silurian become quite thick.

Geologic studies show that nearly all of the Paleozoic formations were progressively exposed to erosion in the old Paleozoic surface, and there is also considerable evidence that nearly all of the Mesozoic formations are in turn in contact at their base with many of these Paleozoic formations. The detection of the many stratigraphic traps that no doubt occur due to the wide range in porosities of the various Mesozoic and Paleozoic formations that are in contact in this unconformable surface presents a challenge to the geologist and geophysicist. This will no doubt be one of the most interesting phases of the development of the area.

USE OF THE REFLECTION SEISMOGRAPH AS AN EXPLORATION TOOL IN THE WILLISTON BASIN

The reflection seismograph has been used in the Williston Basin almost continuously since 1935. The early work consisted of long widely spaced correlation lines running across the basin. The records obtained were, for the most part, excellent and the reliability of these old correlation lines, in light of more recent detail work, is surprising.

The wide reconnaissance correlation program was followed by more closely spaced correlation shot points, generally on every section corner, and by continuous profile lines.

In portions of the basin the correlation method still serves a useful purpose, but most of the work is done by continuous profiling.

Reflection seismograph records selected from each of the locations designated by numbers 1 to 5 on the generalized cross-section are shown in Figure 3. The photographic reproduction of the original records leaves much to be desired, so the figure fails to show the excellent quality of most of the profiles. The correlation of the reflections is indicated, and the records are aligned so that a reflection associated with the Jurassic marked "J" is on a horizontal line. Records 2, 3, 4, and 5 are all related to each other by continuous profiles extending over some 90 miles, and the correlations therefore are believed to be reliable. There are several gaps in the coverage between Records 1 and 2, so the correlation is subject to revision.

The surface instrument spreads used on these records are different. In the shallower portions of the basin a quarter mile split spread is commonly used as shown on Records 3, 4, and 5. A one-third mile split spread was used in the area from which Record No. 2 was selected, and Record No. 1 was shot in an area where 2,200-foot split spreads were used. The long spreads, the shallow reflections, and the erratic weathering make it desirable to use one seismometer per trace and unmixed records.

The time section corresponding to these five reflection records shows the data much more clearly (see Figure 4). The distance between Records 1 and 5 is some 175 miles. The direction of the cross-section changes from northeast to east at Record No. 3. The numbers on the left of the figure indicate the time in tenths of

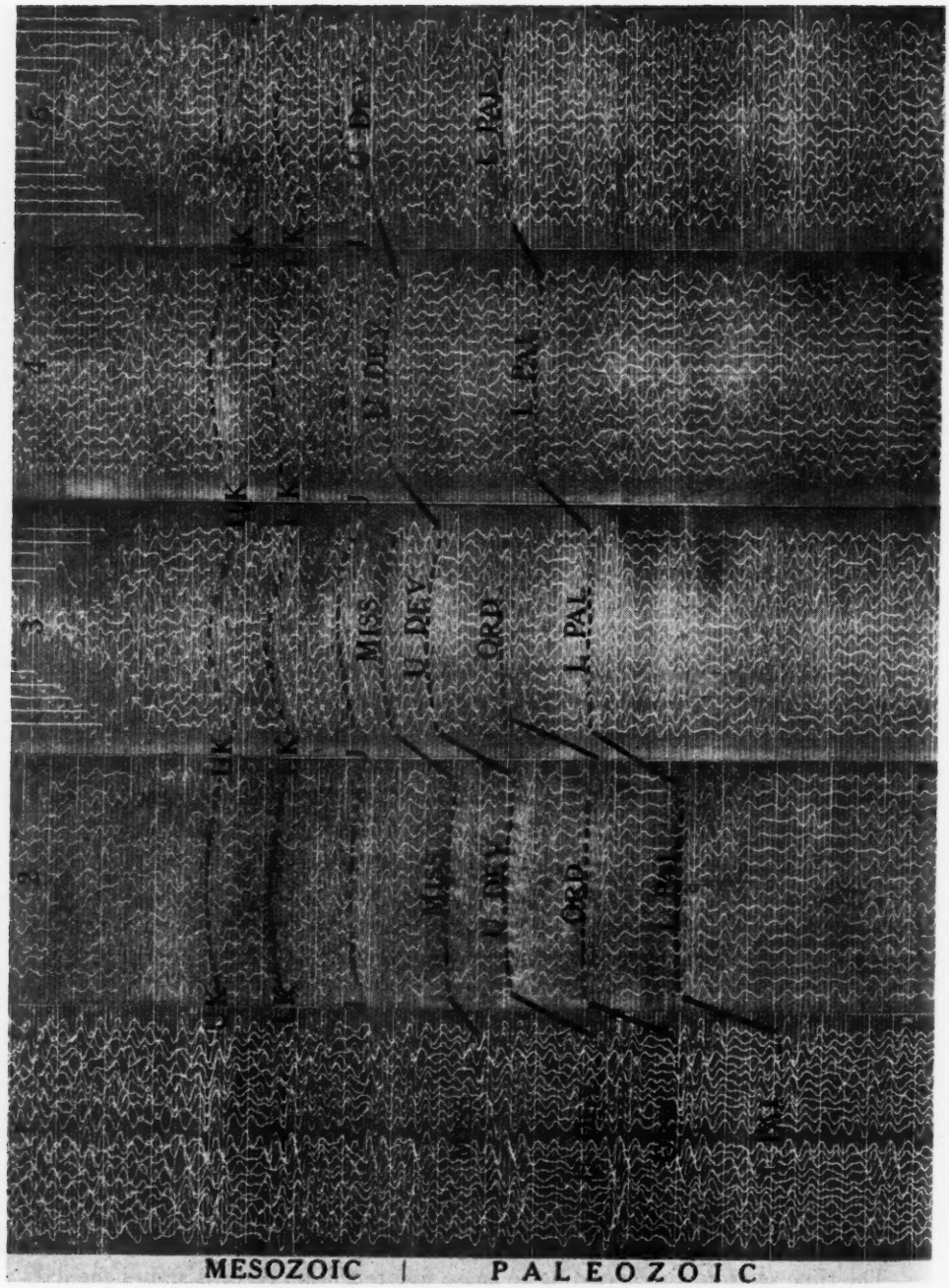


FIG. 3. Seismograph records selected in the areas shown by numbers one to five on the generalized cross-section show the unconformity between Mesozoic and Paleozoic formations.

a second earlier and later than the Jurassic. The westward time divergence between the three top reflections, which are from Mesozoic horizons, is not nearly as pronounced as the divergence of the deeper reflections, which are related to the Paleozoic horizons. The difference in time between the Upper and Lower Cretaceous reflections, designated by UK and LK, increases from 109 to 164 milliseconds. This is a divergence of 55 milliseconds in 175 miles. The time interval between the Lower Cretaceous and Jurassic reflections increases from 111 to 163 milliseconds.

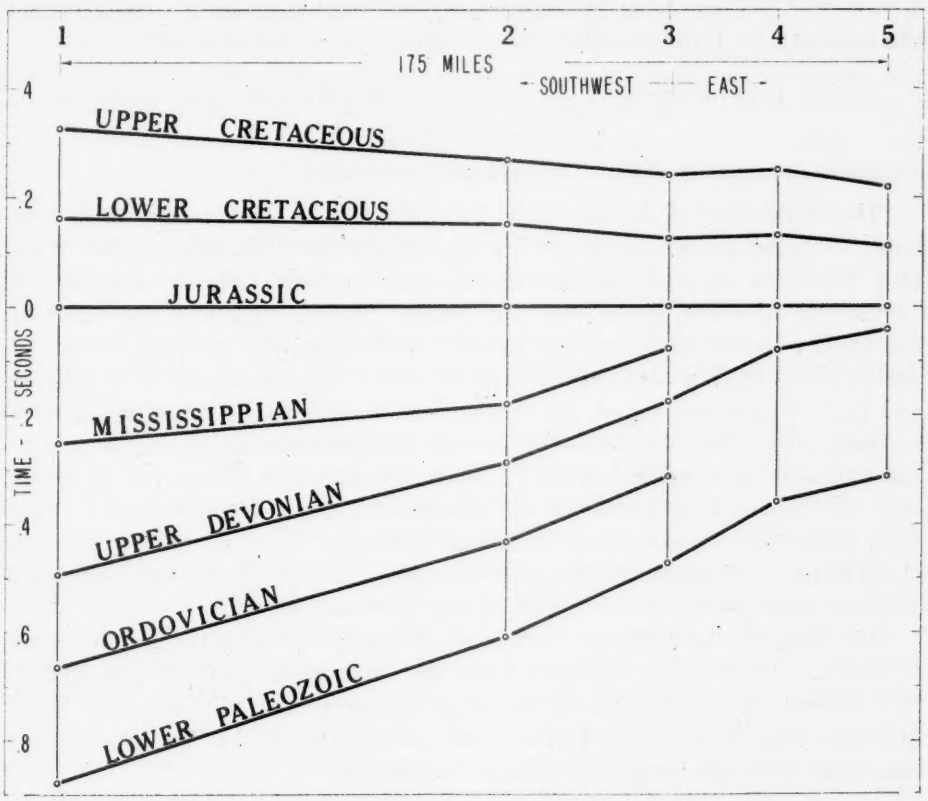


FIG. 4. Time section obtained from the seismograph records of Figure 3 showing travel times with the Jurassic reflection as a reference.

Referring to the Paleozoic reflections, it is observed that the time interval between the Upper Devonian and the Lower Paleozoic reflections increases from 270 to 383 milliseconds. In a much shorter distance the time interval between the Mississippian and Upper Devonian reflections increases from 96 to 244 milliseconds. The divergence between the Jurassic and Mississippian reflections in the same distance is 176 milliseconds. The total time divergence between the Jurassic and Lower Paleozoic reflections is some 570 milliseconds in 175 miles.

Attention should be called to the fact that the figure shows a time section and that the normal increase in interval velocities basinward, when applied to these time data, will result in a depth section showing greater relative divergence.

A comparison of the time section with the generalized cross-section shows that continuous reflections are obtained from horizons above and below the major Mesozoic and Paleozoic unconformity. In local areas reflections are obtained from the unconformity surface itself, and in most areas reflections immediately above and below can be obtained. The correct identification of the reflections in local areas where well and velocity control are not available presents a problem, and the necessity for tying into such control cannot be overemphasized.

DESCRIPTION OF UNUSUAL STRUCTURAL ANOMALIES ENCOUNTERED IN THE WILLISTON BASIN

Paleozoic Topography Reflected in Mesozoic Structures

The topography of the old eroded Paleozoic surface is reflected into the overlying Mesozoic formations to varying degrees, dependent upon a number of factors. The most important of these is probably the little understood differential compaction of sands, shales, and limestones. The magnitude of the Paleozoic topography as well as the regional extent likewise is subject to a number of variables such as the resistance of the exposed surface to erosion and the magnitude and type of erosional forces. An erosion resistant Paleozoic formation may be exposed in the Paleozoic surface as a result of normal homoclinial dip or as a result of structural movement in the Paleozoic formations. It is expected, therefore, that the magnitude and shape of the distortion or drape in the Mesozoic formations above the irregular eroded Paleozoic surface will vary in different portions of the basin, and present knowledge is not sufficient to predict to what extent the Paleozoic topography will be reflected into Mesozoic structure.

The drape in the Mesozoic formations overlying Paleozoic topography would be shown by reflections obtained from the Cretaceous, Jurassic, and Triassic formations. The travel time of the reflections from the Mississippian, Upper Devonian, and Ordovician horizons would be distorted by any velocity anomaly associated with the irregular Paleozoic topography.

Structural Anomalies Due to Reefs

Devonian and Silurian reefs are present in the outcrops in the northeastern edge of the basin in the vicinity of Winnipeg, Manitoba, and it has been reported that reef structures have been penetrated by the drill in various wells drilled in the North Dakota portion of the basin as well as in the Canadian portion.

In the North Dakota portion of the basin reefs would be expected in the Middle Devonian and Silurian, which in this area are composed primarily of limestones and dolomites with very little shale, whereas the Upper Devonian reefs in Alberta are built up in a thick Green Shale section. It would be expected,

therefore, that the magnitude and type of differential compaction occurring in the reef and off-reef sediments would be different in North Dakota than in Alberta. In fact, the opinion has been expressed by various geologists that there will be very little structural distortion of the formations above the reef, wherever the reef mass is built up in a limestone section. Under these conditions the velocity anomaly quite often encountered in the vicinity of a reef mass would probably be quite small. The absence of both structural deformation in the overlying formations and a velocity anomaly severely limits the ability of the reflection seismograph to locate these Middle Devonian and Silurian reefs.

Very little subsurface data have been made available from the many wells drilled in the Saskatchewan portion of the Williston Basin, but sufficient data are available to indicate that these Devonian and Silurian sections are quite different from those in North Dakota. The lithology and tectonic history of the Upper and Middle Devonian and of the Silurian of Saskatchewan and Alberta is discussed by J. B. Webb.[8] He describes a thick deposition of evaporites in these formations and the formation of reefs during this same period of deposition. It appears that the Elk Point formation of East Central Alberta described by J. R. McGehee[9] extends eastward into Saskatchewan with perhaps an increase in thickness. In fact, the Amerada Clarence Iverson well in the vicinity of the Nesson Anticline shows nearly 300 feet of salt in the Middle Devonian which has been tentatively correlated with the Elk Point.

It would be foolhardy to attempt to analyze in detail the ability of the seismograph to detect reefs in the Paleozoic where these rapid changes in thickness and lithology take place. A study of the data at hand indicates, however, that considerable distortion of the sediments adjacent to and above the reef mass does occur and that this distortion extends upward into the Mesozoic formations. It is apparent that although seismic maps showing Mesozoic structure are significant, these maps will not necessarily indicate the nature of a deeper Paleozoic anomaly in these unusual areas. The eventual solution of this exploration problem will require the drilling of many more wells and close coordination between the geologist and geophysicist. Velocity data obtained from surveys made in wells drilled through the evaporite section with special emphasis being placed on the measurements made in the Devonian and Silurian will be invaluable in reaching a solution to this problem.

It is apparent that in many instances it will be difficult and even impossible to differentiate, seismically, between Mesozoic and Paleozoic structure resulting from a reef buildup in the Devonian or Silurian and that caused by a change in the evaporite thickness due to salt movement or flow. The importance of conducting a careful study of the Devonian and Silurian section on both a regional

[8] Op. cit.

[9] J. R. McGehee, "Pre-Waterways Paleozoic Stratigraphy of Alberta Plains, *Bulletin of American Association of Petroleum Geologists*, Vol. 33, No. 4 (April 1949), 603–613.

and local basis cannot be overemphasized. Exploratory wells should be drilled through this section into the underlying Ordovician.

Structural Anomalies Due to Salt Movement

In his article J. B. Webb[10] describes the Elk Point evaporite formation as being 1,700 feet thick in East Central Alberta with three major salt beds having a total thickness of 1,200 feet, the thickest being 450 feet. This salt was deposited during Middle Devonian and Silurian time in a great evaporite basin extending for more than a thousand miles through Manitoba, Saskatchewan, Alberta, and into the Northwest Territory, relatively close to and parallel with the edge of the Pre-Cambrian Shield. It is apparent, therefore, that this is one of the largest known evaporite basins. The possibility of local movements or flow of this salt mass causing a structure in the Upper Paleozoic which would be reflected into the overlying Mesozoic formations must be considered. In this case seismic maps showing Mesozoic structure would be significant, and it should be possible to map the Paleozoic horizons above the salt mass. The seismic maps of the Ordovician and Lower Paleozoic formations below this salt mass would be in error by an amount depending upon the magnitude of the velocity anomaly associated with the change in thickness of the evaporite section.

CONDITIONS AFFECTING ACCURACY OF SEISMIC RESULTS

There are many conditions that affect the accuracy and reliability of seismic reflection work in the Williston Basin. Probably the most serious is the variation of the vertical velocity in the near-surface formations. The pre-glacier surface consists of Tertiary sands and shales which may be as thick as 2,000 feet. This surface was exposed to erosion prior to glacial time, and apparently a large number of stream channels dissected this old Tertiary surface. These channels were filled with reworked Tertiary or detrital material, or with glacial drift. No doubt new channels were cut during each glacial era which in turn were filled with glacial debris. The result is that the Tertiary surface below the drift is traversed by innumerable channels and sinks which are filled by materials having a wide range of velocities. This material should be distinguished from the so-called weathered layer because, for the most part, there is little relationship between the normal weathered layer and these partially buried low velocity zones. Data obtained in up-hole surveys have shown the presence of thick layers of material with a velocity as low as 3,000 feet per second buried beneath 150 feet of normal high velocity near-surface material. In places this buried low velocity layer extends to depths greater than 600 feet. The vertical velocity of this anomalous material varies between 3,000 and 5,500 feet per second and may vary between these limits within a single township. The effect of these near-surface vertical velocity

[10] J. B. Webb, ibid.

variations upon the reflection travel time and the importance of devising an adequate correction procedure is readily apparent.

The Tertiary contains a number of porous sandstone stringers and quite porous coal beds. These porous layers, especially if they outcrop in deep coulees or in bad land topography, tend to drain the interstitial water out of the formations, thereby lowering the vertical velocity. Low velocity zones believed to be due to this phenomenon have been shown by up-hole surveys to extend more than one mile from the outcrop. Quite often these low velocity zones coincide with blind shot holes, which are quite troublesome.

The glacial drift which covers most of the surface of the Williston Basin becomes thicker than 600 feet in some areas, and in many cases the record quality is adversely affected by this glacial mantle.

Conventional up-hole and refraction weathering correction procedures are adequate to handle the routine computations. Supplementary data, obtained wherever necessary, are applied in various ways to take care of the individual problems. These data consist of long refraction shots taken in shot holes one-half to three-half spreads beyond the ends of the split spread.

A typical example showing the nature of the refraction data obtained and their relation to the vertical velocity in the near-surface formations is shown in Figure 5. The first break portion of the reflection record is copied on the left edge of the figure. The time-distance plot to the right shows data obtained from these first breaks and from the same setup recorded in the reverse direction from the next shot point. The records were obtained from 5 pound shots at a hole depth of 46 feet. Two seismometers per group ten feet apart were used, and the group interval was 150 feet.

The vertical velocity through the near-surface formations is shown by the up-hole plot on the right of the figure. In this example the up-hole survey showed only 15 feet of weathered material having a velocity of 1,500 feet per second. The unweathered layer having a vertical velocity of 5,900 feet per second was only 50 feet thick. An intermediate velocity layer some 116 feet in thickness with a vertical velocity of 3,000 feet per second is directly above a second high speed layer having a velocity of 6,500 feet per second.

The peculiar character on the first breaks is typical of records obtained where these intermediate velocity zones are present. Energy transmitted through the the shallow refractor at the base of the weathered layer is attenuated rapidly with distance as shown by Traces 1 through 5. On the other hand, the deeper 6,500-foot per second layer carries considerable energy so that good breaks are obtained on Traces 6 through 16, and strong second breaks can be observed on Traces 4 and 5.

A ray diagram is shown at the bottom of the figure, drawn according to the vertical velocity pattern shown on the up-hole survey. The refraction travel times applicable to each of the depicted ray paths were computed and are presented on the refraction time-distance graph by the solid lines. The close agree-

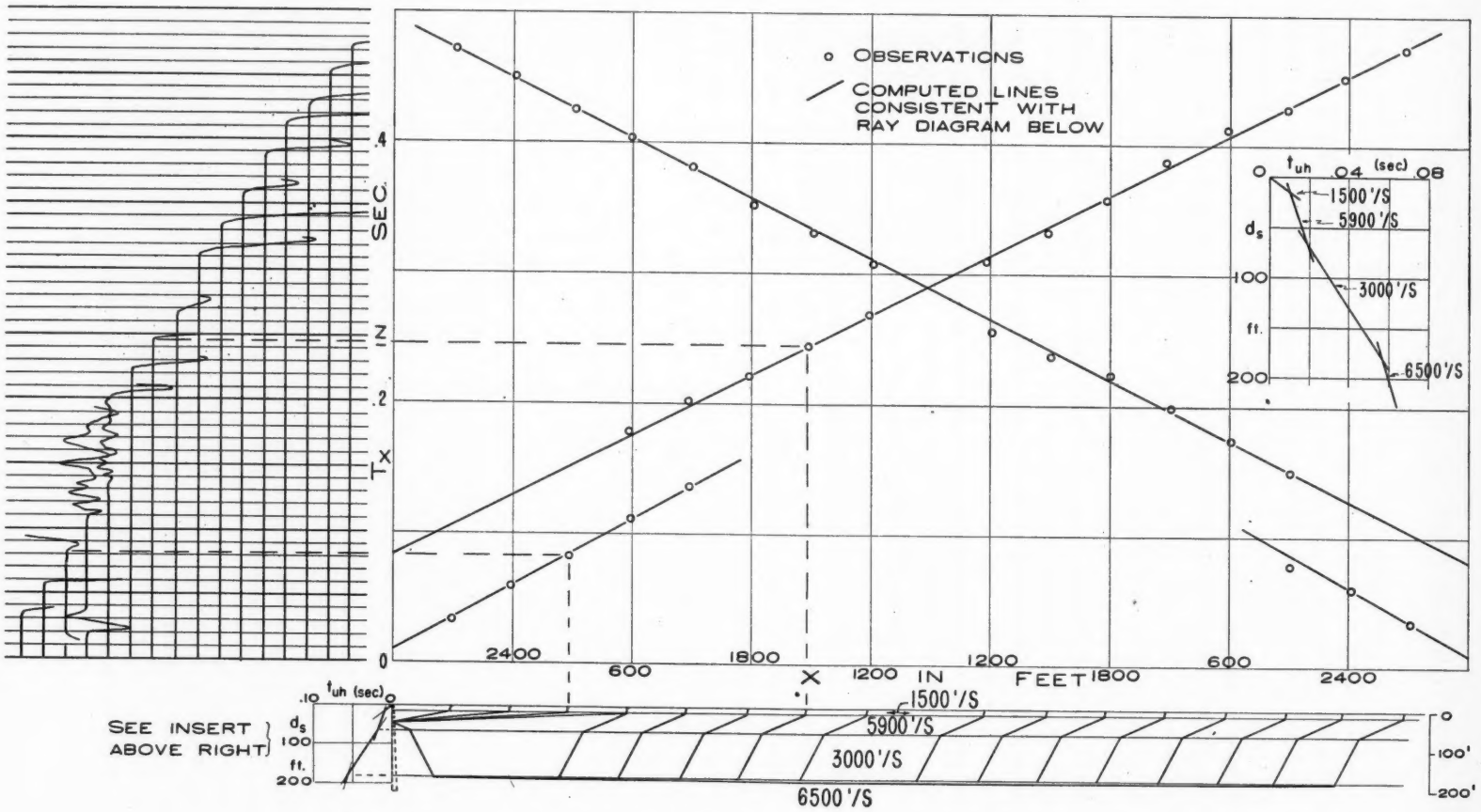


FIG. 5. Refraction and up-hole data confirm the presence of a buried low velocity layer.

ment between the computed and observed times indicate that the predicated horizontal layering is one solution for the time-distance data.

It can be noted from a study of many records that the refraction energy travelling within the layer below the base of the weathering is attenuated very rapidly with distance and that the low frequency components of the first break energy are attentuated much more rapidly than the higher frequency components. This indicates that the 50-foot layer acts as a high pass filter, which suggests that this layer acts as a wave guide. Computation of refraction and up-hole data

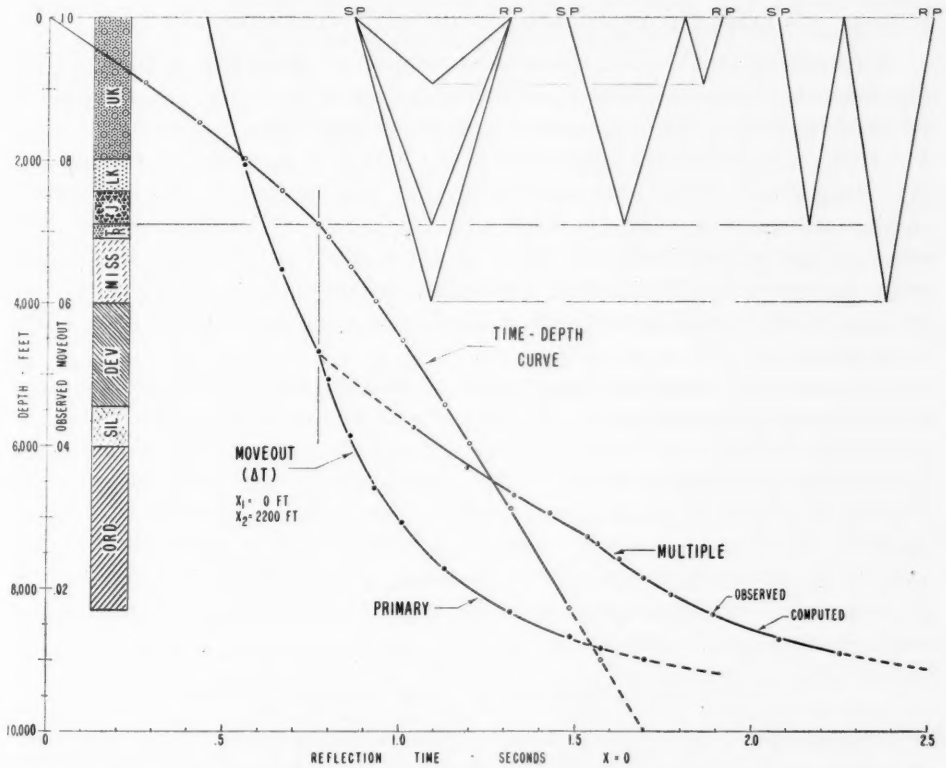


FIG. 6. An analysis of reflection moveouts (delta T) indicates that multiple reflections are present.

obtained from many other profiles in the area shows that the intermediate velocity layer is rather consistent and that it, as well as the high speed layer above, varies in thickness. It has been noted that the frequency content and amplitude of the first breaks are affected by these variations in thickness. A study of the refraction and up-hole data in the portions of the prospect where the first breaks have normal character shows that only the 5,900- and 6,500-foot per second layers are normally present and that the intermediate velocity layer is present only in the areas of anomalous first breaks.

The refraction data normally obtained by shooting in the holes beyond the end of the spread, in the manner previously outlined, is very useful in locating velocity anomalies in the surface formations. However, the seismologist will immediately recognize the fact that up-hole data obtained in the survey of deep holes drilled through these intermediate velocity layers are required to determine the thickness and travel time through these layers. It should be emphasized therefore that the first or primary usefulness of the refraction data is to locate the anomalous areas, and further analysis is required to arrive at a unique correction.

EFFECT OF TOPOGRAPHY IN THE CRETACEOUS SURFACE

A correction problem is introduced in portions of the Williston Basin by the fact that the Cretaceous surface, consisting in turn of the sandstones and lignitic shales of the Hell Creek, of the sandstones and greenish-gray marine shales of the Fox Hills, and of the thick gray shales of the Pierre[11] was exposed to erosion during a long period. This Cretaceous topography was covered by Tertiary formations consisting of the marine sands and gray shales of the Fort Union. The effect upon reflection travel time of variations in the thickness of the Fort Union or in the elevation of the buried Cretaceous surface depends upon the relative vertical velocities of the lower part of the Tertiary and the upper portion of the Cretaceous.

In some areas it has been found useful to map this eroded Cretaceous surface by supplementary refractions. This map should be examined to determine any coincidence between the Cretaceous surface and the indicated seismic structure in the deeper Mesozoic formations. A complete study requires vertical velocity data in the Upper Cretaceous and Tertiary formations. It is common practice to drill core holes at carefully chosen locations to confirm a seismic structure prior to deeper drilling. Vertical velocity surveys should be run in each core hole to confirm the velocity assumptions made in the seismic refraction computations and reflection time corrections.

MULTIPLE REFLECTIONS IN THE WILLISTON BASIN

The quality of the reflection records in the Williston Basin, for the most part, is quite good, and many subsurface formations can be mapped over considerable distances. In many regions, however, the seismologist is quite often misled by the apparent good quality of reflections, and the Williston Basin is no exception. The conditions, outlined by various authors,[12] that are favorable for the generation of multiple reflections are certainly prevalent in the Williston Basin because there is a large velocity contrast near the Mesozoic-Paleozoic contact which produces an abnormally strong reflection. In general, the presence of multiple re-

[11] These formation names are used in North Dakota.

[12] *Geophysics*, Vol. XIII, No. 1 (January 1948).

flections is the rule, rather than the exception, and in certain portions of the basin this can be quite troublesome.

A delta T[13] analysis of a number of profiles was made in an area where multiple reflections were believed to be present. A total of 120 profiles was used in the analysis. The average delta T was determined for each of a number of correlatable reflections, rather than from a random statistical averaging process. The resulting moveout or delta T curve, shown in Figure 6, is a normal curve for the reflections above the Paleozoic. It was noted, however, that data obtained from the Paleozoic reflections could be divided into two groups. One group had an abnormally large moveout or delta T, whereas the other group had a more normal moveout. The reflections having the abnormally large moveout have been identified as multiple reflections.

The observed moveout was used to compute the time-depth relationship shown in the figure. It is noted that a change in slope of the time-depth curve and a corresponding velocity contrast occurs near the base of the Mesozoic.

It is natural to suspect that this velocity contrast, from which a strong reflection is obtained, would serve as a source for multiple reflections. The assumption was made that the energy returning to the surface in the strong Lower Mesozoic reflection was reflected downward. This downward travelling energy was presumably reflected upward by each of the Mesozoic and Paleozoic reflecting horizons, as indicated in the figure. Using the data from the time-depth curve, the normal moveout of each of these multiple reflections was computed and plotted as shown by the solid line. The agreement between observations and computations tends to confirm the assumption.

In the areas where the reflection quality is good, long spreads can be used. There is then a considerable difference between the moveout times of the primary and multiple reflections. Discriminating between the primary and multiple reflections on the basis of the moveout time differences, however, is quite difficult over a considerable portion of the basin because the multiple reflections arrive at the same time as the Lower Devonian, Silurian, Ordovician, and Lower Paleozoic primary reflections. The interference pattern generated by the multiple, with its greater moveout, and the primary reflection is quite disturbing and complicates the interpretation of reflections whose sources are at or near reef depth.

REQUIREMENTS OF AN EFFECTIVE SEISMIC EXPLORATION PROGRAM

The seismic exploration program in the Williston Basin, to be effective, should be designed to recognize and solve the various problems outlined. Many of the problems are not amenable to a unique solution, especially at this stage of development. Having recognized these problems, however, the seismologist

[13] As used in this paper delta T or observed moveout refers to the increase in reflection travel time due to a specific increase in spread distance.

and geologist would be amiss if they fail to collect supplementary data that would assist in their solution.

The problems encountered in the exploration of the Williston Basin can perhaps be divided into two general groups:

First: Those related to the interpretation of the Paleozoic horizons.
Second: Those related to the near-surface correction problem.

The problems related to the interpretation of the Paleozoic horizons can be approached in a more logical manner if the exploratory wells are drilled into the Ordovician or through the Elk Point formation and a careful study of the evaporite section is made. A velocity survey should be made in every well penetrating these formations with observations being closely spaced in the Paleozoic section. The reflections obtained from depths equivalent to the Devonian and Silurian tend to be inconsistent and hard to interpret. The seismologist needs to know more about these sections and their velocities in order to decide whether these anomalous reflections are related to insignificant facies changes, salt movement, or reef development.

The problems related to the near-surface correction will be solved by learning more about the Tertiary and Upper Cretaceous formations. The collection and analysis of well and core samples should be extended to include a detailed study of the Tertiary and Upper Cretaceous formations. Velocity surveys should be obtained in each core hole with closely spaced determinations, and the results should be compared with the analysis of the Upper Cretaceous and Tertiary lithology. Velocity surveys made in wells should include a careful measurement of the vertical velocity in the shallower formations by taking more closely spaced determinations.

SALT SOLUTION, A SEISMIC VELOCITY PROBLEM IN WESTERN ANADARKO BASIN, KANSAS-OKLAHOMA-TEXAS*

M. B. WIDESS†

ABSTRACT

Solution of salt from a shallow Upper Permian formation in parts of Western Anadarko Basin was observed to produce a pronounced and relatively abrupt velocity change, such as to cause over 300 feet of seismic relief error across a distance of less than three miles. Core-hole velocity shooting and velocity profiling were used in the study of the effect of salt solution. The theory, methods, and results of the velocity profiling program are described. The core-hole velocity data indicate that in the area several environments are present which involve different types of velocity alteration by ground water activity. This kind of phenomenon is considered to be of general significance and related to the spurious representation of surface topography sometimes observed in seismic structural maps.

I. INTRODUCTION

Of the many purposes for which accurate seismic velocity data may be required in seismic interpretation, none is more important than to detect rapid lateral variations of the velocity in the geologic section. Because geologic structures of oil reservoirs are usually relatively local features, their mapping by seismic methods may be seriously confused when sharp and pronounced lateral velocity variations occur in the area.

In recent years, very strong lateral velocity variations have been found in conjunction with some bioherm reefs. This is a seismic velocity problem related to lateral *lithologic* variations which occurred during the deposition of the sediments. A totally different cause of rapid lateral velocity variation is identified, not with facies differences in the original sediments, but with irregular or abrupt *alteration* of a deposit which was originally regular. Such an effect can be severe when vulnerable bedding is shallow enough to come under the influence of ground water action.

The weathering layer is the common manifestation of velocity alteration by ground water (and the atmosphere). The importance of lateral variation of depth and velocity of the weathering layer is well recognized. What is sometimes overlooked is the possible effect of ground water on the underlying beds. One of the most striking examples is the alteration of shallow salt-bearing beds, as illustrated in the present paper. The problem however is general and is not restricted to salt basins.

1.1 Salt Solution in Western Anadarko Basin. A considerable amount of salt was originally present relatively uniformly areally in the section between the

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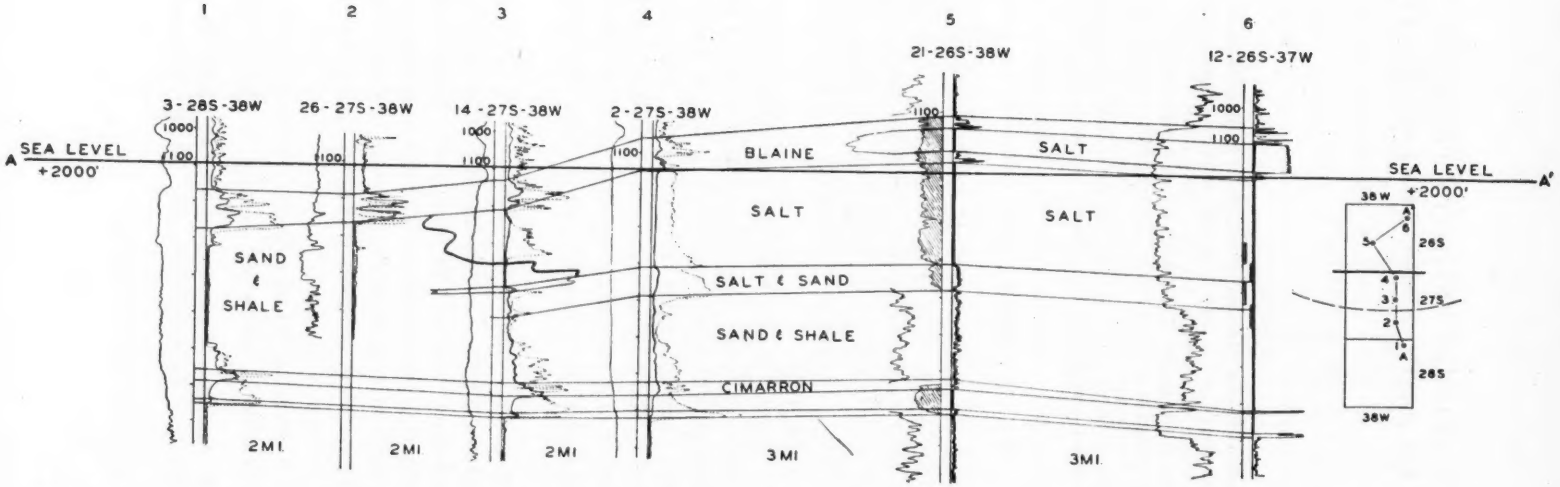


FIG. 1. A cross-section in Grant and Kearny counties, Kansas, illustrating solution of salt in the Blaine-Cimarron interval. The salt shown in Wells 5 and 6 is removed in Wells 1 and 2, the overlying section thereby slumping by over 200 feet. (After Moore.)

Blaine and the Cimarron formations (Upper Permian) over a large part of Western Anadarko Basin. The salt-bearing formation subsequently came under the influence of ground water activity. The resultant cause of a velocity problem is apparent from the cross-section in Figure 1.* The cross-section, prepared for wells in the Hugoton Field area, in Grant and Kearny counties, Kansas, illustrates the lack of areal uniformity of salt content which now occurs in the area. At the two right-hand wells on the cross-section the salt is intact, while at the two left-hand wells essentially all the salt has been removed by solution, causing the overlying section to slump by over 200 feet. Removal of the high-velocity salt and its associated mineralization resulted in a marked change in the velocity of the over-all section, a change which can be areally abrupt.

Two extensive salt basins, in parts of which the salt is essentially intact, are now present in the general area.† The cross-section in Figure 1 applies to the northwestern of the two basins. The area covered by the velocity investigation to be described is associated with the southeastern salt basin, and is shown in Figure 7. The northern portion of the general area is also known as the Dodge City Basin.

1.2 The Case History. The seismic velocity problem in the area is presented as a case history. It pertains to an extensive seismic velocity survey conducted by the Stanolind Oil and Gas Company in the Dodge City Basin in Kansas about ten years ago and followed by sampling of velocity south in Oklahoma and Texas.

The velocity problem in the area was originally revealed by a seismic map on a Pre-Permian horizon obtained in the Dodge City Basin. The map showed a curiously unreal plateau involving a steep flank which extended for over fifty miles. Since shallow salt was known to be present, suspicion of the map led to examination of the area with respect to geologic markers from core holes. It was then discovered that the Cimarron marker showed no semblance of the seismic plateau, whereas the Blaine, many hundreds of feet above the Cimarron, displayed the same plateau as the seismic map. Evidently the seismic map reflected very strongly a change in velocity of the section between the Cimarron and the Blaine—the section which is salt bearing.

In order to determine whether the salt was entirely responsible for the seismic plateau, core holes to the Cimarron were drilled on the opposite sides of the steep flank of the plateau, and these holes were shot for velocity. The core holes picked up much salt on the plateau and essentially none off the plateau. The core-hole velocity data showed a velocity change which accounted, within the limits of accuracy of the data, for all of the seismic relief across the flank of the plateau. The matter of proving the spuriousness and explaining the cause of the seismic plateau was evidently closed.

* D. F. Moore, "Geology of the Permian Salt in Western Anadarko Basin, Kansas-Oklahoma," submitted for publication in the *Bull. Amer. Assoc. Petrol. Geol.*

† D. F. Moore, op. cit.

The seismic velocity problem as such, however, was now only opened. In particular, it was necessary to evaluate the seismic structural maps already completed on the seismic plateau—which plateau we shall henceforth call "the salt basin." With the known profound velocity change occurring across the flank of the salt basin, one was confronted with the possibility that significant velocity anomalies might be present *within* the basin.

The simplest solution to this problem in seismic mapping is to avoid the problem by preparing isopach maps using only horizons below the salt. Unfortunately, though isopaching with respect to the Cimarron was possible to the north of the subject area, the Cimarron reflection deteriorated as the critical area of salt was approached so that isopaching had to be abandoned.

Another mode of attacking the velocity problem was considered. As already stated, the Cimarron, being essentially below the salt, is not appreciably affected by salt solution, while the Blaine is. The change of Blaine-Cimarron interval thickness is therefore diagnostic of changing salt content and therefore of velocity changes. Presumably, therefore, whether or not appreciable velocity changes are liable to be encountered can be indicated by whether or not the Blaine-Cimarron interval thickness varies sufficiently. Though this was used, it was felt that there was not adequate control from available core holes and that a direct velocity determination was desired.

A program for mapping the velocity by using velocity profiling was therefore undertaken for the Dodge City Basin. (A ΔT-analysis, that is, determining velocity from reflection move-outs appearing on the available records of the production seismic survey, was out of question because of the very short seismometer spreads which had been used.) The objective at that time was to obtain only a general velocity picture of the area, sufficient to test the acceptability of the seismic map as a whole rather than to check any one local structural feature.

This phase of the work, the theory of velocity profiling and its consequent application and results, are described in the second part of this paper. Suffice it to say for the present that no rapid velocity change was observed in the tested area within the salt basin in Kansas. The abrupt change of velocity on the flank of the salt basin was easily detected and agreed in magnitude with that observed by the core-hole velocities previously obtained.

The relative simplicity of the velocity picture in the Dodge City Basin in Kansas was not necessarily construed as being representative of that entire salt basin in Western Anadarko Area. Therefore, when subsequently the Company had occasion to apply the core drill for structural information at a number of locations in the Texas Panhandle and northwestern Oklahoma, the opportunity for additional velocity control was recognized and used. Several distinct local areas were tested by core drilling and many of the holes were shot for velocity. Contrary to the observations by velocity profiling in the Dodge City Basin, marked local variations in velocity were observed in some parts of Texas

within the salt basin. The core-hole velocity program, the results and their implications, are presented in the third part of this paper.

2. VELOCITY PROFILING SURVEY IN THE DODGE CITY BASIN

Velocity profiling has most of the variations in techniques which are generally associated with conventional seismic reflection surveying and has many other variations as well. It is not uncommon to utilize a shooting method in velocity profiling which permits several independent analyses for velocity. Such a flexible system was used in the Dodge City Basin; its purpose was to determine the most accurate method applicable there. To make the evaluation, it was first necessary to recognize the theoretical segregation of the various sources of error with respect to each possible velocity profiling method. Since past literature is not explicit on this point, we shall devote a large part of this section to a fundamental comparison between velocity profiling methods.

2.1 Theory of Velocity Profiling

Velocity profiling is substantially a method of triangulation in which reflec-

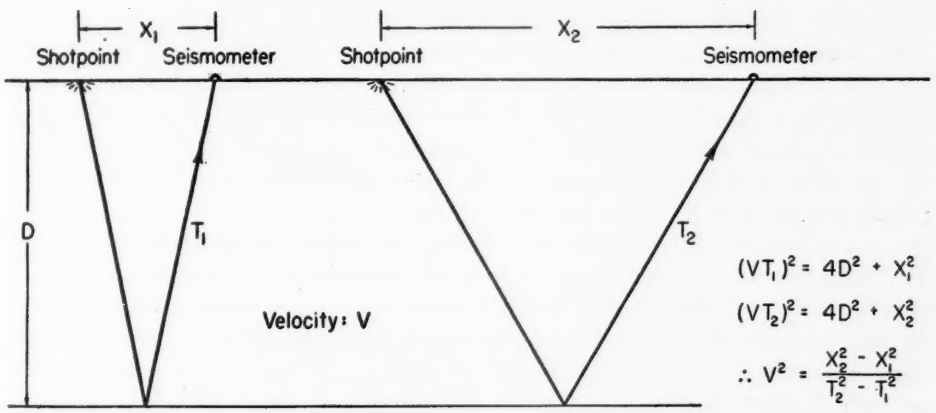


FIG. 2. Elemental generalized form of velocity profiling, the starting point in the design of velocity profiling methods.

tion time and horizontal distance at the surface constitute the observations; the sectional velocity being determined is necessarily that which provides closure in the geometric triangulation.

Basically, the triangulation may be made from any two reflection times (for a specific reflector) which are obtained for different shotpoint-to-seismometer distances. This is illustrated in its most elemental and simplified form in Figure 2, where the reflector and the surface are horizontal and the velocity is uniform. Depth and velocity both being in question, the two equations permit solution for both these variables. The velocity equation may be written

$$V^2 = \frac{X_2^2 - X_1^2}{T_2^2 - T_1^2} = \frac{X_2^2 - X_1^2}{2T_m \Delta T_x} \qquad (1)$$

where V is the velocity, ΔT_x is the difference in the idealized reflection times, and T_m is the mean of the reflection times. Usually T_m is so much greater than ΔT_x that effect of errors in determining T_m is minor compared to the effect of errors in determining ΔT_x. The problem of establishing velocity accurately therefore lies primarily in the measurement of ΔT_x. This term we shall here call "distance delay"; some companies, including Stanolind, use the term "normal move-out."

The simplicity of Figure 2 is of course not realized in practice, particularly because of a number of disturbing effects on the measurement of ΔT_x. We shall segregate the disturbing effects on ΔT_x into two categories, those which are intrinsic to all methods of velocity profiling and those which can be avoided by certain methods of velocity profiling.

2.11 Intrinsic Sources of Error in Measuring ΔT_x. These disturbing effects, aside from errors in picking (timing) reflections, are the following two: (1) the curvature (or bending) of the reflection wave path and (2) the dip of the reflecting bed. The first effect is usually of appreciable magnitude and a correction for the curvature may be applied to the velocity which is computed on the basis of straight-line paths.* The second effect requires a comment in explanation. There are actually two effects associated with dip of the reflecting bed. One of these effects results from the fact that the two incidence points in Figure 2 would then be at a different depth, thereby introducing a possibly sizeable difference in the two reflection times. This effect is discussed later because it can be eliminated. The second effect of dip is that which results even when the *same* incidence point is used for both the short and the long shotpoint-to-seismometer distances (see for example Figure 3C), and is an effect intrinsic to all velocity profiling methods as such. A $\cos^2\theta$ term then appears on the right-hand side of Eq. (1), where θ is the dip of the bed. Fortunately the effect is usually negligible because locations of relatively gentle dip are usually chosen for velocity profiling. If necessary, dip may be determined by conventional seismic methods and a correction for the presence of that dip then applied to Eq. (1) or its equivalent.

2.12 Controllable Sources of Error in Measuring ΔT_x. We now proceed to the types of disturbing effects, that is, sources of error, which are controllable to a degree by the particular method of velocity profiling which may be used. It is on this basis that the preferred method in a given area may be selected.

* W. E. Steele, Jr., "Comparison of Well Survey and Reflection 'Time-Delta Time' Velocities," *Geophysics*, Vol. VI (October 1941), 373.

E. J. Stulken, "Effect of Ray Curvature Upon Seismic Interpretations," *Geophysics*, Vol. X (October 1945), 473.

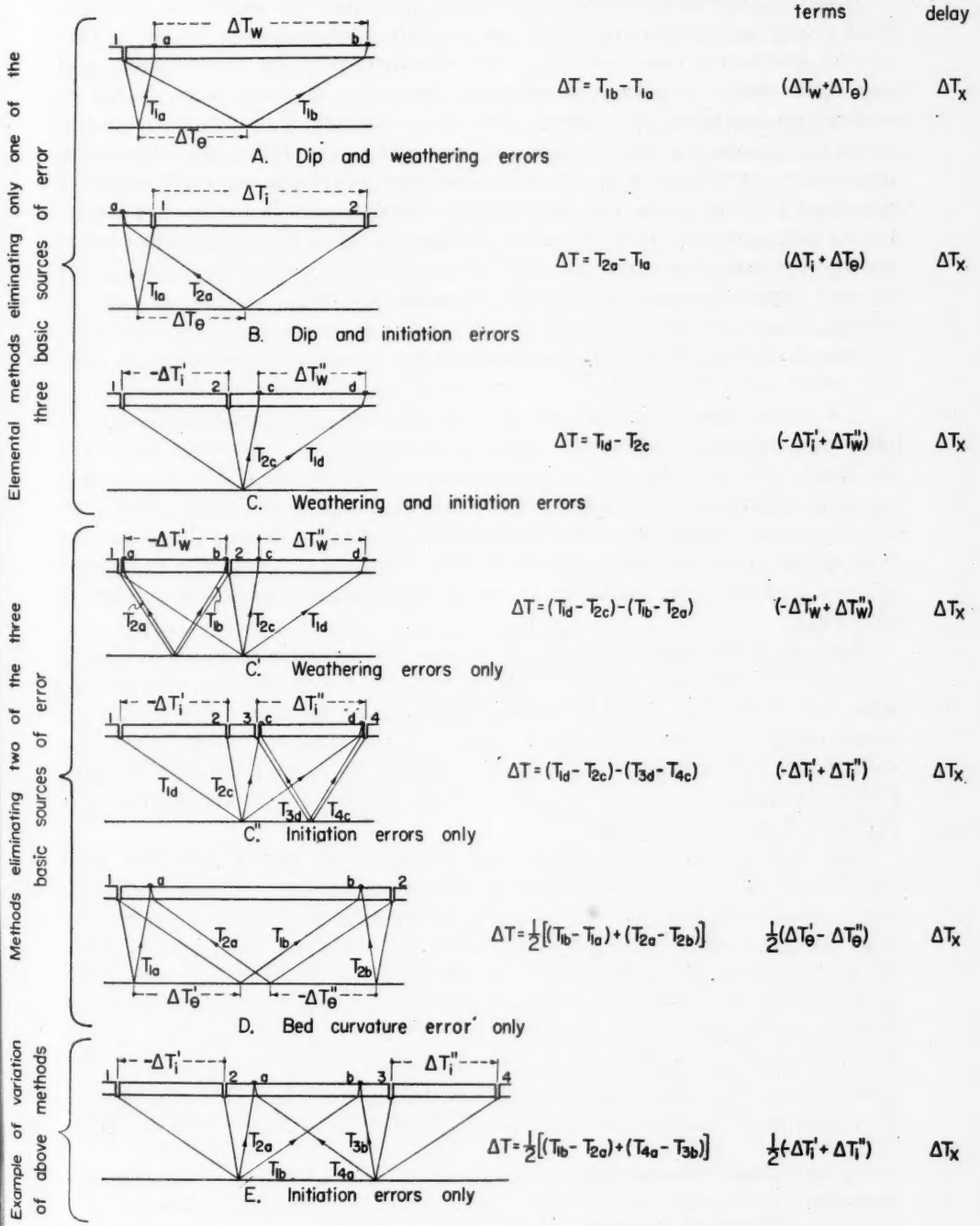

Equation for gross difference in reflection time
Contents of gross time - difference
Error terms
Distance delay
Elemental methods eliminating only one of the three basic sources of error
Methods eliminating two of the three basic sources of error
Example of variation of above methods
A. Dip and weathering errors
B. Dip and initiation errors
C. Weathering and initiation errors
C'. Weathering errors only
C". Initiation errors only
D. Bed curvature error only
E. Initiation errors only

FIG. 3. Illustration of the principles in velocity profiling methods by which various basic sources of error can be eliminated. ΔT_x is the distance delay used to compute velocity. The basic sources of error are ΔT_θ, ΔT_w, and ΔT_i, namely, dip of the bed, weathering error, and initiation error respectively, the terms being used in their broad sense.

There are three effects to be considered in this category, as follows. The first is the change of reception conditions at the two seismometers in Figure 2. This includes weathering time corrections and adjustments to the datum plane, and such other effects as change in reflection frequency resulting from change in seismometer locations. The second effect is the change of initiation conditions at the two shotpoints. This includes adjustments to the datum plane and such other effects as difference in reflection character and difference in time delays associated with the shots. The third effect is the difference in the level of the reflecting bed at the two incidence points in Figure 2. Most velocity profiling methods, and the ones to be considered here, are designed for reversed shooting (either reversed surface coverage or reversed subsurface coverage), so that in cases of uniform dip of the reflecting bed, this effect of dip is essentially cancelled out. Curvature of the reflecting bed however is not necessarily cancelled out. The third effect to be considered is therefore the curvature of the reflecting bed.

The above three basic kinds of effects will be designated respectively by the following generalized or symbolic terms which fall nearest to common usage: (1) weathering time difference ΔT_w, (2) initiation time difference ΔT_i, and (3) curvature time difference ΔT_c. Though efforts may be made to determine these time differences and thereby use them to correct the observed reflection time data, the three effects are nevertheless sources of error. The choice of optimum method of velocity profiling rests primarily on which of these three effects is subject to least error.

Any one of the three basic sources of error can be easily eliminated. Clearly initiation time difference ΔT_i is eliminated by using a common shotpoint and the same shot to obtain T_1 and T_2. Analogously, weathering time difference ΔT_w is eliminated if the same seismometer, instead of the same shotpoint, is used for both T_1 and T_2. The effect of curvature in the reflecting bed is eliminated by using a common incident point for T_1 and T_2. These three methods are illustrated in Figures 3 A, B, C respectively.

One can advance a step further and eliminate any two of the three basic sources of error. This is accomplished by using more intricate arrays of shotpoints and seismometers. For example, to eliminate effects of both initiation and reception, one may combine the types of layouts shown in Figures 3A and 3B to obtain the method illustrated in Figure 3D. To eliminate the effects of both weathering and curvature, the types of layouts shown in Figures 3B and 3C may be combined to obtain the method illustrated in Figure 3E.* To eliminate the effect of both initiation and curvature, the shotpoints in Figure 3E may be replaced by seismometers and vice versa. Variations to these methods will be described presently. Only error due to bed curvature remains in the method of Figure 3D; only initia-

* L. W. Gardner, "Vertical Velocities from Reflection Shooting," *Geophysics*, Vol. XII (April 1947), 223.

———, "Seismograph Prospecting," Patent #2,231,575, issued Feb. 11, 1941.

tion errors in Figure 3E; and only weathering errors in the above counterpart to Figure 3E, the meaning of these error terms being again considered in a generalized sense.

At this point, one may ask whether it is possible to design a method of velocity profiling by which all three of the basic sources of error are eliminated. The answer of course is no; that is, when reflection times only are used, it is impossible to differentiate distance delay ΔT_x from (1) weathering error ΔT_w, (2) initiation error ΔT_i, or (3) bed curvature ΔT_c. This statement is analogous to the following statement pertaining to conventional seismic structural mapping: when reflection times alone are used, it is impossible to differentiate structural dip from (1) weathering error or (2) initiation error (the isopaching method being here excluded because it measures only *relative* structural dip). The proof for these statements can be readily perceived from the geometry of combinations of reflection rays.

2.13 Generalized Reflection-Ray Pairs. In order to make intelligible the comparison between the various profiling methods, we shall first briefly examine the fundamental relations between the components of *any* reflection time difference, that is, any pair of reflection rays (for the same reflector). A reflection time difference may refer to two times on the same record, then usually called "move-out" (or "step-out"), or else the two times may be picked on difference profiles.

The various effects which make up a reflection time difference have already been discussed. As a first order approximation, we separate the four basic effects by expressing reflection time difference ΔT as the sum of each of the four terms, namely,

$$\Delta T = \Delta T_\theta + \Delta T_w + \Delta T_i + \Delta T_x. \tag{2}$$

These terms are each used in the broad sense defined in the preceding section; that is, ΔT_θ pertains to depth difference of the two incidence points for the same reflector, ΔT_w includes all effects peculiar to the two receptors, ΔT_i includes all effects peculiar to the two shots, and ΔT_x pertains to the effect of the two shotpoint-to-seismometer distances for the same reflector. The first three terms are identified with specific points on the ground surface in that they refer to specific shotpoints and/or seismometers. The fourth term, namely ΔT_x, we tentatively assume is a function of distance as such, the same function for all of the vicinity.

It is interesting to note that any pair or set of pairs of reflection rays which provides one or a set of reflection time differences may be theoretically reconstructed by adding or subtracting two classes of ray pairs, such as are shown in Figure 4. In Class I, a pair of seismometers receive from the *same shot*, the seismometers being on either or both sides of the shotpoint. In Class II, shotpoint and seismometer positions are interchanged to provide essentially the *same path* below the levels of the shots. (The choice of these two classes as basic is arbitary; other types may be used, but in any case two classes are necessary.) The reconstruction is executed by subtracting or adding a sequence of ray pairs, where a

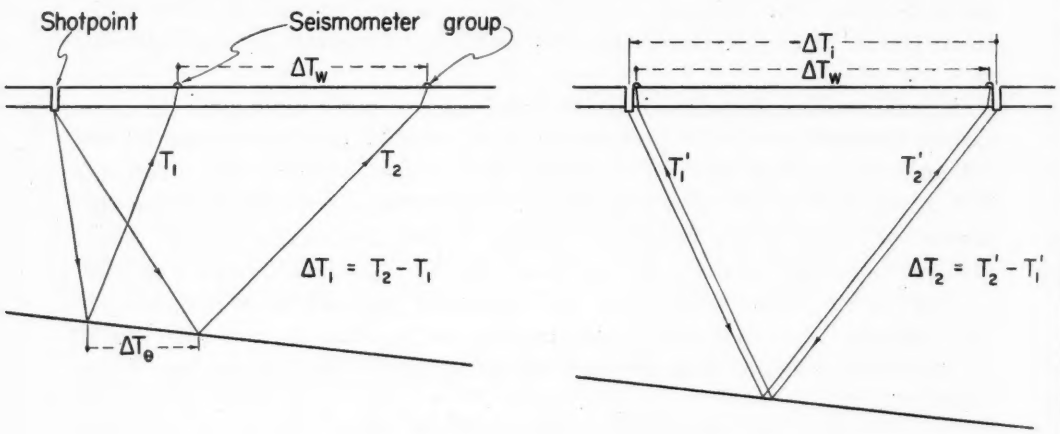
common ray is drawn for each step of the sequence. The fact that all reflection time differences can be reconstructed from only two classes of ray pairs is pertinent to the design of velocity profiling methods in that it prescribes a limit to the kinds of useful interrelations between reflection times which can occur.

The equations for the two classes of reflection time differences are as follows:

$$\text{Class I:} \quad \pm\Delta T_1 = \Delta T_\theta + \Delta T_w \pm \Delta T_x \tag{3}$$

$$\text{Class II:} \quad \pm\Delta T_2 = \Delta T_w - \Delta T_i. \tag{4}$$

In the equations and referring to Figure 4, positive values mean increased positive magnitude in the positive direction. For example, positive ΔT_w means



Class I: Reflection time difference obtained by using the same shot for two separated seismometer groups:

$$\Delta T_1 = \Delta T_\theta + \Delta T_w \pm \Delta T_x$$

Class II: Reflection time difference for a pair of reversed rays of essentially the same path (below the shot levels):

$$\Delta T_2 = \Delta T_w - \Delta T_i$$

FIG. 4. Two basic classes of reflection-ray pairs. All reflection time differences may be reconstructed by adding or subtracting the configurations of these two classes of ray pairs.

greater "weathering" term in the positive direction. The term ΔT_x is positive if the shotpoint-to-seismometer distance is greater for T_2 than for T_1. This system of notation will be used in describing the various velocity profiling methods.

From Eq. (4) it is evident that we can replace weathering time difference by initiation time difference whenever we so desire. This is of practical significance because it permits us to make the substitution of one source of error for the other

by simply using reversed rays. Actually the substitution can be done in two ways. The first method is illustrated by comparing Figure 3A with Figure 3B. Here the shotpoints and seismometers are all interchanged in order to provide the change-over from weathering error to initiation error. The second method is illustrated in the comparison between Figures 3C and 3C′. Here a set of reversed rays is introduced. In Figure 3C′ the difference in reflection times for the reversed rays is added to the ΔT of Figure 3C, so that the initiation difference is eliminated and only weathering differences remain. An analogous procedure is shown in Figure 3C″ wherein only initiation differences remain. The reflection time difference for reversed rays is of course essentially the same as the mistie between interlocking traces in conventional continuous profiling, and correspondingly this time difference is generally determined for the average of many reflections rather than from only that reflection which is used for the measurement of ΔT_x.

It is noted that the methods in Figures 3C″ and 3E are both sensitive only to initiation errors. Of the two methods, the one in Figure 3C″ is considered preferable in practice primarily because of the greater simplicity of its field operations.

2.14 Theoretical Comparison between Velocity Profiling Methods. For each velocity profiling method shown in Figure 3, the equations are given for the gross time difference which is to be used. This time difference equals the distance delay ΔT_x, which is sought, plus the error terms. The distance delay and the error terms are shown under separate tabulation in the figure. For comparison purposes, the magnitude of shotpoint-to-seismometer distances, X_1 and X_2, are considered to be respectively the same for each velocity profiling method treated.

It is apparent from Figure 3 that the concept of curvature error when referring to dip of a bed is directly applicable to similar concepts of curvature error for weathering and for initiation. Just as in Figure 3D no error results in ΔT_x if the bed has uniform dip, so in Figure 3C′ no error results in ΔT_x when weathering error is linear with distance, and in Figure 3C″ when initiation error is linear with distance.

The question now arises as to which kinds of errors are equivalent, that is, for which kinds of errors are all the methods shown in Figure 3 equally accurate. From this consideration one can obtain insight as to which method may be the most accurate on the average for a given area. The answer to the question is readily obtained. For the usual cases, the distance delay ΔT_x is approximately a parabolic function of distance, being proportional to the difference in the square of the two shotpoint-to-seismometer distances for which the time difference is measured. We shall treat the error terms in an analogous parabolic form. Let the weathering error t_w vary along a line according to the relation $t_w = k_w x^2$, where x is the distance of a seismometer from a specific reference point, and k_w is the parabolic constant; the differential weathering error is the difference in t_w at two seismometers, that is, $\Delta T_w = t_w' - t_w''$. Correspondingly, let the expression for initiation error t_i be $t_i = k_i x^2$, where x is the distance of a shotpoint from the same reference point, and $\Delta T_i = t_i' - t_i''$. Assuming that no correction for bed curvature

is applied, we designate by t_θ the dip error which is equal to twice the change in reflection depth from a specific reference point divided by velocity. As before, we consider a parabolic expression for dip error: $t_\theta = -2k_\theta x^2$, where x is the distance of the incidence point from the same reference point, and $\Delta T_\theta = t_\theta' - t_\theta''$. Note should be made of the negative sign and the factor of two. For all three parabolic equations, the reference point from which x is measured is the point of symmetry of a symmetric layout, such as Figures 3C, D, E, and is the same for Figures 3C′ and C″ as for Figure 3C. The reference points for Figures 3A and B are at the shotpoint and seismometer respectively. If now the parabolic constants are made the same,

$$k = k_w = k_i = k_\theta, \tag{5}$$

one can easily derive that the error terms shown in Figure 3 for the various velocity profiling methods are all the same, and equal to $(k/2)(X_2^2 - X_1^2)$. (The distances X_1 and X_2 are respectively the same for all methods in Figure 3.) We can therefore state the following theoretical generalization: all the methods of velocity profiling (using the same X_1 and X_2 distances respectively) are equally accurate if the above parabolic constants are equal.

It is departure from this equivalence which in practice will favor one method of velocity profiling over another. Basically, the comparison is between magnitude of weathering, initiation, and bed-curvature errors over a specific span of surface coverage, as when comparing methods of Figures 3C′, C″, and D. When span of coverage is considered a variable, one must bear in mind that as the span is lengthened, generally the error increases from curvature of the reflecting bed, whereas weathering errors, which are usually random with distance, may not so increase. Therefore with everything else being equal, velocity profiling may become increasingly more accurate for longer spans if only weathering or initiation errors are involved but may be no more accurate if only bed-curvature errors are involved. This applies also to the method of Figure 3E and to other such variations wherein the spans over which weathering, initiation, or dip errors are involved are widely separated.

2.2 Application of Velocity Profiling in the Dodge City Basin

2.21 Field Comparison between Velocity Profiling Methods. The velocity profiling methods shown in Figures 3C and D are the ones most commonly described in literature. The former usually also includes a reversed ray for which the outside shotpoint and seismometer positions are interchanged. The primary purpose of the additional shotpoint is for weathering control for the nearby seismometer. Also, X_1 is made small in order to avoid the need for an additional inside shotpoint. In principle, the two methods, Figures 3C and D, are sometimes referred to as the reversed subsurface coverage method and the reversed surface coverage method respectively.

When the velocity profiling program was undertaken in the Dodge City Basin,

emphasis was placed on a multi-method of profiling by which a number of independent computations of velocity could be made in order to determine which class of method was most accurate and to provide checks on the data. A spread arrangement suitable for the purpose is shown in Figure 5. This is recognized as a combination of the methods illustrated by Figures 3C′, C″, and D. It consists of a pair of conventional interlocking profiles, together with a split-spread profile shot into the same spread from its midpoint. As already described, the pairs of

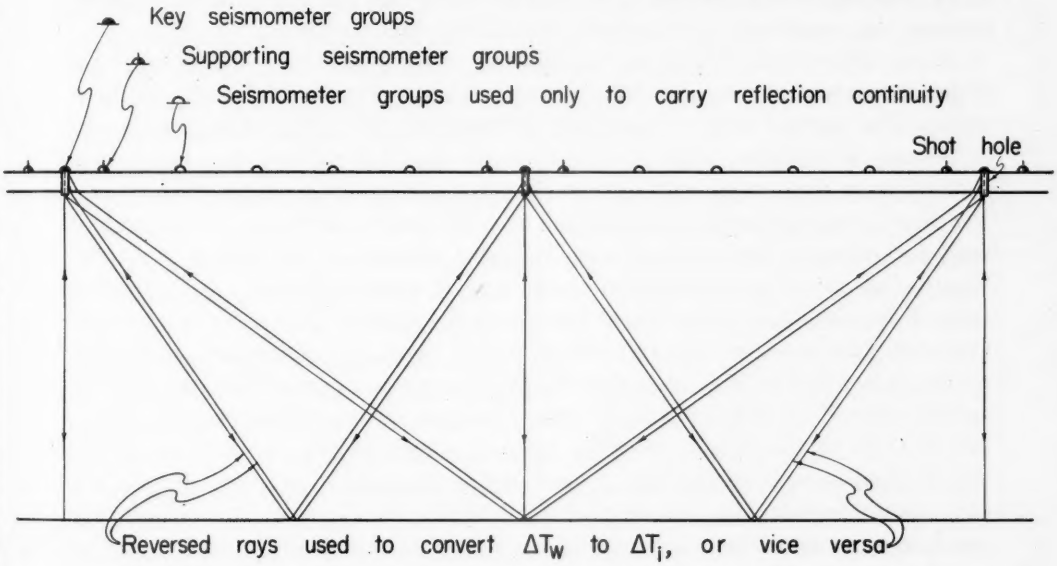

Key seismometer groups
Supporting seismometer groups
Seismometer groups used only to carry reflection continuity
Shot hole
Reversed rays used to convert ΔT_w to ΔT_i, or vice versa

FIG. 5. A multi-method of velocity profiling. Velocity can be computed by several independent methods; which one of the three basic sources of error remains in the computation depends only on the manner of handling the recorded reflection times, as shown in Figures 3C′, C″, and D.

essentially identically reversed rays between adjacent shotpoints serve to transform weathering differences into initiation differences or vice versa, as desired.

Because of the relatively shallow sedimentary section in the test area, the spread lengths were made short compared to that usually identified with velocity profiling. The spacing between outside shotpoints in Figure 5 was about 2,500 feet.

The data was computed in three ways, such that of the three basic sources of error (weathering, initiation, and bed curvature), only one was effective for each computation.

In evaluating relative merit of the several methods, there is necessarily the question of criteria which can be applied. A positive and certain criterion was not available. It was found that accuracy could not be gauged reliably by the scattering of points on the $X^2 - T^2$ curve obtained for an individual profile. Also, a comparison against well velocity at any one location could not serve the purpose because the objective at hand was to measure lateral changes in velocity rather

than to measure absolute velocity, and it was therefore not desirable to introduce the problem pertaining to the difference between well velocity and profiling velocity, a discrepancy which is observed in most areas.* Well velocity control in the area was inadequate to establish a lateral velocity gradient which could serve as a check. The criterion which was adopted in the Dodge City Basin was therefore based on shooting two proximate velocity profiles, the spreads of the two profiles being mutually perpendicular. The most accurate method was considered to be the one which yielded most similar velocities for the pair of velocity profiles, the comparison being made statistically over the area.

It was determined from this test that the profiling method which is sensitive to bed curvature as the only basic source of error provided definitely the best results. The method is that illustrated in Figure 3D. The effect of bed curvature in the area is therefore markedly less than the errors in determining weathering corrections or the errors resulting from change of initiation conditions of the shots. The weathering methods tested included up-hole times to seismometers ultimately used for reflection timing, and also included refraction weathering methods. Weathering correction was determined to each of three seismometers comprising each of the three key seismometer groups on the spread. Considerable care was taken with the weathering correction, primarily because, judging from published results, it was first believed that velocity profiling methods sensitive to weathering errors rather than to bed curvature would provide most accurate velocity measurement. As to the velocity profiling method sensitive only to initiation errors, this method was promising only in portions of the general area tested. In other portions of the area, the method resulted in highly erratic data even though care was taken to refer reflection timing to the first shot at a given depth in order to avoid the noticeable increase of reflection time with successive shots at the same depth.

Since a method sensitive only to bed curvature proved to be the most accurate, the intermediate shotpoint in Figure 5 was actually not necessary. It is therefore interesting to find that the most accurate method for the area is also the most simple, both in spread layout and in interpretation.

2.22 Handling of Data. In the idealized illustrations of velocity profiling methods in Figure 3, only the minimum number of seismometers are shown, and theoretically it is only for these seismometers that the elimination of indicated sources

* C. H. Green, "Velocity Determinations by Means of Reflection Profiles," *Geophysics*, Vol. III (October 1938), 295–305.

W. R. Ransone and F. Romberg, "Average Vertical Velocities from Refraction and Reflection Profiles," *Geophysics*, Vol. VI (April 1941), 158–167.

W. E. Steele, Jr., op. cit., 370–377.

B. G. Swan, "Local Areal Distribution of Velocities in the Texas Gulf Coast," *Geophysics*, Vol. VII (October 1942), 367–392.

L. W. Gardner, op. cit., 221–228.

of error results. In practice however it is desirable to time the reflections on additional record traces so as to average out errors associated with picking inaccuracy, even though the initial timing is carried to say half milliseconds (as was done by using 2 millisecond timing lines). One means of providing the additional timing is to introduce additional shotpoints and spreads into the systems. Such a method was initially tested in the Dodge City Basin, using as many as nine shotpoints in a line, and separated nonuniformly to provide even spacing of data on the X^2 scale of the X^2-T^2 plots. Experience showed that use of more shotpoints than was minimum for the tested method was not an efficient procedure of velocity surveying. For locations where inaccurate results were obtained, it was found that the problem was not necessarily resolved by simply adding a large number of auxiliary shotpoints. The effort required for auxiliary shotpoints was more profitably expended instead in shooting minimal velocity profiles at *additional* locations (but not sacrificing on the over-all shotpoint-to-seismometer distance).

Particularly for the velocity profiling methods involving a minimum number of shotpoints, the employment of what we call "supporting seismometer groups" was useful in providing additional reflection times for velocity computations. Supporting groups are shown in Figure 5 and constitute one group on each side of the key group opposite each shotpoint. Additional supporting groups could also be used if desired. The reflection times for the key groups and the supporting groups constitute the only reflection times which were used on X^2-T^2 plot for determining the velocity. Only the *relative* weathering correction from the supporting groups to their intermediate key group is needed, and this is obtained directly from the reflection time differences observed on a common record shot from the proximate shotpoint. Since all three groups are close to this shotpoint, the distance delay involved is generally known within a very small fraction of a millisecond. Also, since the average for many reflections is used, this differential weathering correction can generally be determined to a higher precision than is necessary.

In considering the theory of velocity profiling in Sect. 2.11, reference was made to two possible sources of error which are intrinsic to all velocity profiling methods, namely (1) curvature of ray paths and (2) dip, as such, of the reflector. The second effect was negligible in the area.* The first effect was not. However, since relative velocity rather than absolute velocity was required, this source of error was not significant. A correction of about 250 ft/sec for velocity to a depth of 4,000 feet was applied to the data.

* For the method of Figure 3D, the velocity equation including uniform dip θ is

$$V^2=2(X_2^2-X_1^2)(\cos 2\theta)/[(T_{1b}^2-T_{1a}^2)+(T_{2a}^2-T_{2b}^2)],$$

the times having been corrected to the datum plane.

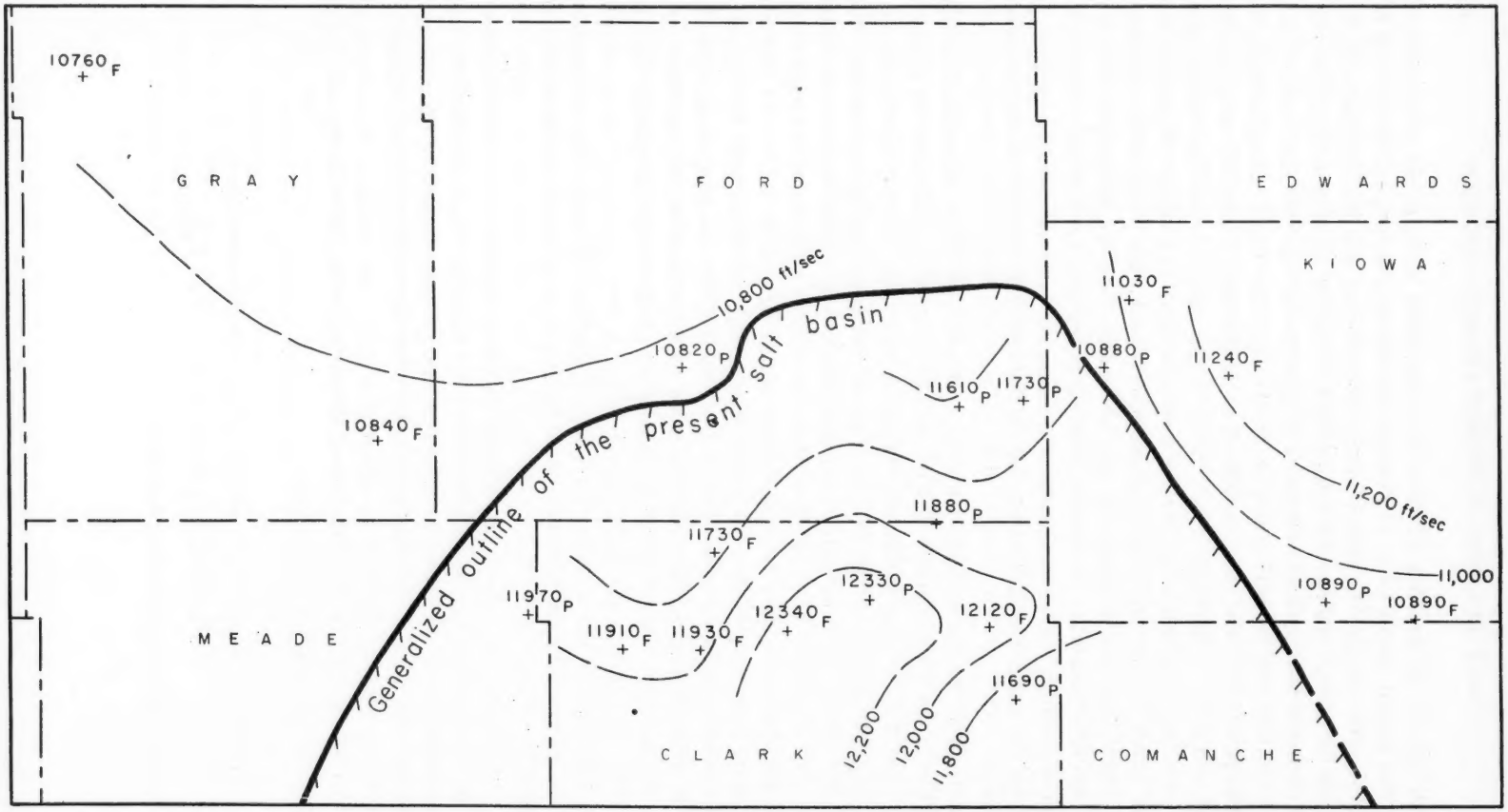


FIG. 6. Velocity map of the Dodge City Basin, Kansas, determined from velocity profiling. The average velocity is to approximately the Topeka horizon, which is at an average depth of about 4,000 feet in the area.

In addition to these factors which affect the distance delay ΔT_x, certain factors have to be considered with respect to the measurement of T_m in Eq. (1). Two factors fall in this category. (1) The reflections are picked in the most reliable leg, namely, a well-developed trough or peak, rather than at the reflection onset, the latter however being the true time to which the reflection time difference should be referred. The reflection time T_m was therefore adjusted to the estimated reflection onset. (2) The second factor pertains to the datum plane. To the first order of approximation, assuming that the wave paths in the weathering layer are vertical and that X_1 is near zero, the datum plane to which reflection times T_1 and T_2 are adjusted for use in Eq. (1) is midway between the shot level and the base of weathering for the T_2 ray. (If the weathering layer is thick, the fact that wave paths are not vertical in the weathering layer may have to be taken into account in determining the datum level.) To relate the velocity from the various velocity profiles, a second datum plane may be used to which the computed sectional velocity is adjusted. For this purpose, a flat datum plane over the large area could not be used because of the pronounced change in surface elevation resulting from the Cimarron River breaks; a varying but relatively smooth datum surface was therefore employed over the area.

2.3 Results of Velocity Profiling in the Dodge City Basin

A velocity map prepared on the basis of velocity profiling is shown in Figure 6. The mapped velocity is to approximately the Topeka formation (some 500 feet above the Lansing) at an average depth of about 4,000 feet, the level at which best reflections were recorded and about 2000 feet above the Arbuckle (Ellenberger).

It was stated that the reliability of velocity profiling was gauged primarily by the degree of consistency between the velocities derived from two velocity profiles whose spreads were near each other and were mutually perpendicular. On this basis, the probable error of the velocity to approximately the Topeka horizon determined from an individual velocity profile was found to be about 150 ft/sec (root-mean-square error of about 220 ft/sec). The probable error of the average velocity for each pair of velocity profiles is therefore about 110 ft/sec. Only those pairs of velocity profiles for which the difference of velocity was less than 400 ft/sec are used in Figure 6. The (weighted) average of the velocity for each pair of velocity profiles is shown in the figure, together with a relative grade of estimated reliability.

The hachured line in Figure 6 marks the approximate limit of the present salt basin, as determined by core-hole logs, the salt being on the hachure side of the line. The velocity profiling data agrees with this limit. As much as 1,200 ft/sec difference in velocity occurs across the west edge of the salt basin.

There is no abrupt change of velocity apparent within the salt basin proper or within the area outside the salt basin. Some lateral velocity gradient is present, but it does not appear to exceed 100 ft/sec per mile within the salt basin.

This amounts to a structural tilt of about 1/3 degree at a depth of about 4,000 feet.

Seismic surveys in the subject area therefore appear to be essentially free of rapid lateral velocity changes, provided that the edge of the salt basin is avoided. As will be pointed out presently, this fortunate condition does not apply to all of the salt basin. Very strong velocity changes were observed by core-hole velocity surveys in the salt basin farther south, in Texas.

3. EFFECT OF SALT SOLUTION IN WESTERN ANADARKO BASIN

Velocity in Western Anadarko Basin was sample tested by core-hole velocity surveys after the serious velocity change across the edge of the salt basin was un-

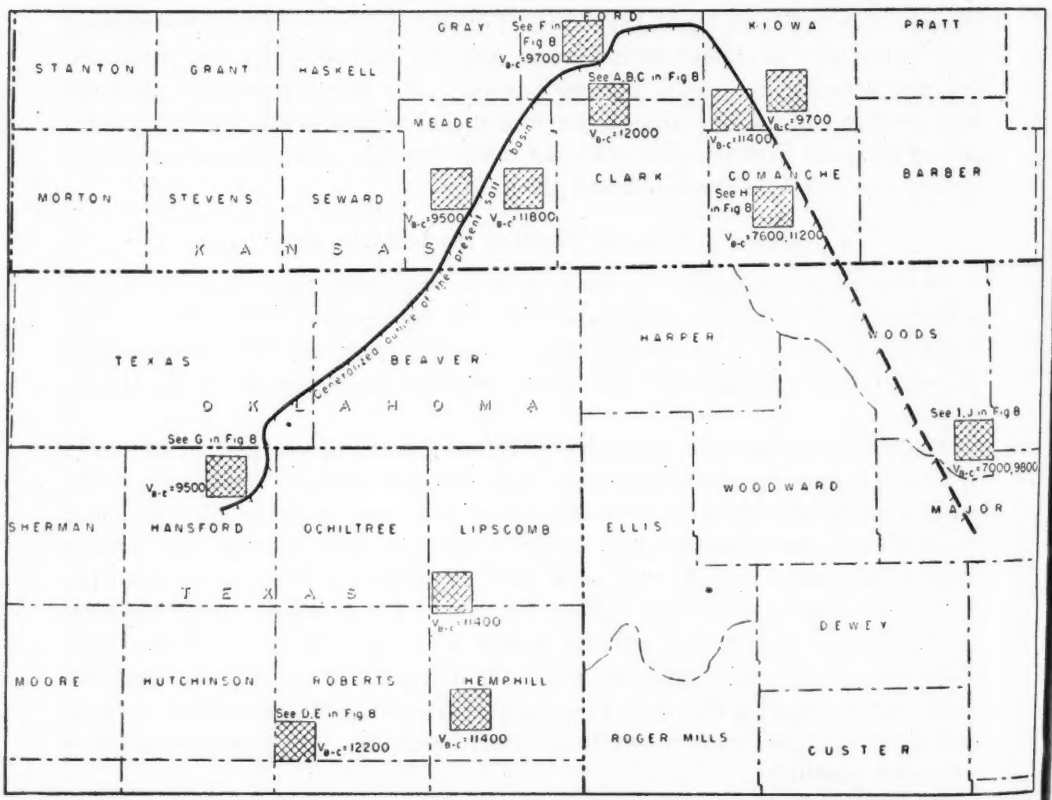


FIG. 7. A plat of a portion of Western Anadarko Basin. The squares indicate areas in which core holes were shot for velocity. The observed velocity V_{B-C} for the Blaine-Cimarron interval is shown for each area. Note that for areas within the salt basin, this velocity is relatively high (11,700 ± 500 ft/sec), even though some locations involve considerable salt solution. The velocity for areas off the salt basin is markedly lower (9,600 ± 200 ft/sec). To the east, the velocity of the upper portion of the Blaine Cimarron interval is much lower. These three magnitudes of velocity suggest three different environments of mineralization pertaining to ground water.

covered. It was suspected that though velocity was reasonably uniform within the salt basin proper in the Dodge City area, other regions of the salt basin might involve considerable velocity change.

The general area over which core holes were shot for velocity is shown in Figure 7. The locations of the core holes are indicated by crosshatched squares, each of which contained from two to eight velocity surveys. The outline of the salt basin is indicated by the hachured line. The solid portion of the line was determined from core-hole logs, while the dashed portion is a generalized extrapolation based on the core-hole velocity, as described in the following sections.

Some remarkably consistent aspects of the velocities were observed when comparing the core-hole velocity data in the various areas, suggesting that several distinct types of velocity alteration occur because of ground water activity.

3.1 The Three Velocity Provinces

In Figure 7 the velocity V_{B-C} for the interval from the top of the Blaine to the top of the Cimarron is shown opposite each area shot for velocity. For some cases, this interval consists of two velocity zones. Two values of velocity are then shown, the first value applying to the shallower of the two zones. Within the limits of accuracy of the data, the velocity was observed to be constant throughout each velocity zone.

Note that all of the velocity values shown in the figure fall into three orders of magnitude: (1) the high velocity of $11{,}700 \pm 500$ ft/sec in the salt basin; (2) the lower velocity of $9{,}600 \pm 200$ ft/sec outside the salt basin; and (3) the still lower velocity of $7{,}300 \pm 300$ ft/sec for the upper velocity zone in the eastern area, both in and outside the salt basin.

It is significant that the high velocity of about 11,700 ft/sec applies to locations in the salt basin even though considerable salt solution and slump occurs for some of these locations. It appears therefore that presence of considerable mineralization maintains the high velocity in the salt basin area. Outside the salt basin, the degree of mineralization is much less, and this different environment of mineralization and loss of salt is associated with the reduced velocity of about 9,600 ft/sec. In the eastern area, a third environment of mineralization occurs which is superimposed on the other two environments. The eastern area is one in which the Blaine is near the surface or is outcropping. Here the Blaine-Cimarron interval is reduced in velocity to about 7,300 ft/sec but only down to the level to which apparently recent action by ground water has taken place.

3.2 Effect of the Lateral Velocity Variation on Seismic Mapping

The preceding section described the generalization of velocity variation over the present salt basin and its environs. With this background, we proceed now to consider the effect of the velocity variation on seismic maps. Since representation of individual structural features is the objective of seismic mapping, usually

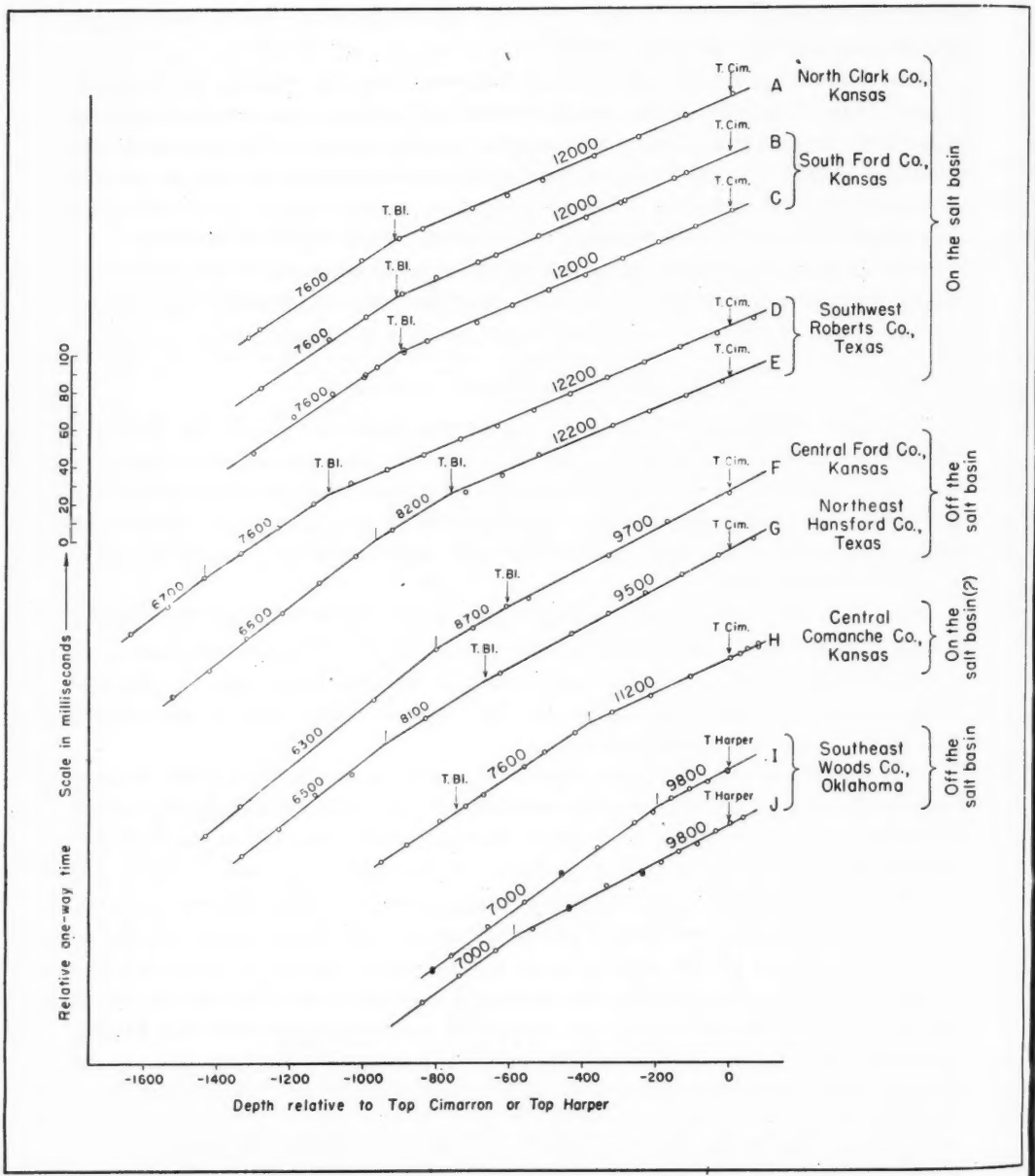


FIG. 8. Examples of time-depth curves from core-hole velocity surveys. Depth is relative only, and the data extends up to about the base of weathering. The various types of velocity change in the Blaine-Cimarron interval are illustrated. See Figure 7 for locations of the core holes.

regional variation of velocity is of minor importance. Of principal importance is the degree and abruptness of relatively *local* variation in velocity, and it is this aspect which will be considered here. To indicate the extent of local variation in velocity, Figure 8 is presented for individual core-hole velocity surveys. (The time-depth curves begin at a point near the base of weathering.) The set of curves illustrates the various types of velocity variation observed in the area for the Blaine-Cimarron interval. These are described as follows.

3.21 The Salt Basin Proper. In the salt basin proper the question is whether severe slumping occurs sufficiently abruptly as to cause serious error in local seismic relief. The conclusion reached by velocity profiling in the Dodge City Basin is that no such abrupt change occurs. This is exemplified by essentially similar time-depth curves A, B, C (Fig. 8) which were obtained from core holes about six miles apart in Ford and Clark Counties, Kansas. That such uniformity is not always present in the salt basin is shown by time-depth curves D and E for two locations in Roberts County, Texas. Here the Blaine-Cimarron interval thickness changes by about 350 feet over a distance of less than three miles. The velocity change associated with the salt solution produces about 50 milliseconds erroneous seismic reflection relief of underlying beds, which is about 300 feet relief error at a depth of about 4,000 feet.

3.22 On the Edge of and Outside the Salt Basin. The velocity outside the salt basin is exemplified by time-depth curves F and G in Figure 8. The locations for these two core holes are in central Ford County, Kansas, and in Hansford County, Texas, respectively, about 100 miles apart. Despite this very wide separation, the velocities are much the same. Evidently no significant velocity problems occur for locations outside the salt basin.

Seismic prospects which fall across the edge of the salt basin are of course particularly vulnerable to considerable error in seismic relief. Not only does the Blaine-Cimarron interval change in thickness but also the velocity of that zone changes. This is shown by curves C and F for locations which are five miles apart and straddle the edge of the salt basin. The seismic horizon at about 4,000-foot depth indicated a relief error exceeding 300 feet over a distance of less than three miles crossing the edge of the salt basin.

3.23 The Eastern Area of Two Velocity Zones in the Blaine-Cimarron Interval. Superimposed on the above two environments which are primarily associated with the salt basin and the area outside the salt basin respectively is the third environment of mineralization. This is illustrated in Figure 8 by time-depth curves H in Comanche County, Kansas, and I and J in Woods County, Oklahoma, all in the eastern area of Figure 7. As already commented, the eastern area is one in which the Blaine is near the surface or is out-cropping, the Blaine-Cimarron interval being reduced in velocity to about 7,300 ft/sec down to the level to which apparently recent action by ground water has taken place, leaving the underlying section practically unchanged. For curve H, the lower member of the Blaine-Cimarron interval retains the relatively high velocity, 11,200 ft/sec, associated

with the salt basin. For curves I and J, the lower member of the interval has a velocity of 9,800 ft/sec, which identifies the locations as being outside the salt basin province. This velocity data is the basis for the dashed line in Figure 7, which therefore provides only an extrapolated maximum eastern limit that the salt basin may reach.

Curves I and J are particularly significant because we can consider them without alluding to salt. Two important features are involved. The first is that the alteration of velocity occurs to a depth exceeding 600 feet. The second factor, even more important in so far as seismic mapping is concerned, is that the level to which the alteration occurred is not uniform over the area, the level differing by about 300 feet at the two locations which are about six miles apart. In this case about 25 milliseconds erroneous seismic relief results from the change of level of alteration. The relief in the level of alteration is totally unrelated to the relief of the shallow strata. The observations therefore indicate that velocity alteration by ground water action is not confined to shallow levels and that a fairly sharp change in the level of alteration can occur, a phenomenon which may happen without the matter of salt coming into the picture.

4. VELOCITY ALTERATION BY GROUND WATER IN GENERAL

4.1 Scope of the Effect of Ground Water on Velocity. Alteration of velocity in a formation by ground water activity is vividly demonstrated by the weathering layer. Though sometimes the base of the weathering layer is coincident with the water table, it is important that usually the base is lower, and often considerably lower, than the existing water table. Therefore whether or not water fills the interstitial volume is usually not the feature which distinguishes the abnormally low velocity of the weathering layer from the much higher velocity of the subweathering zone. The low velocity must consequently be attributed to ground water percolating downward and dissolving all or some of the mineralization which binds the grains of the clastic sediments; considerable time is required to dissolve the mineralization, so that when the water table drops, the weathering base may not drop unless the lower water table persists for a long period. Generally the base of the weathering layer would be expected to be the level reached by the last relatively stable ground water table. Certain exceptions to this generalization may occur, as for example when the water table rises temporarily and the weathering base also rises coincident with the water table, and here the presence of water in the interstitial volume is responsible for raising the velocity.*

Since the geophysicist defines the weathering layer only by its abnormally low velocity, while the geologist has in the past made little use of seismic velocity, there is some disagreement in the concept of the weathering layer. A reconciliation between the terminologies would be of great mutual benefit.

* P. L. Lyons, "The Low Velocity Layer in Seismic Exploration," *The Mines Magazine* (November 1946), 501.

So much for the weathering layer. Potentially, ground water is also an agent for velocity alteration in formations below the weathering layer whenever the water is in a leaching or depositional environment. Though solution of salt is an outstanding example, the velocity alteration can be prominent for other cases, notably illustrated in Woods County, Oklahoma.

In some areas, ground water movement occurs at depths exceeding many thousands of feet, so that the resultant velocity alteration by water activity may occur at very great depths. The potential velocity alteration however may not be realized, and even salt beds at moderate depth may be left intact, as has already been described. Broadly speaking, the effect of ground water action would be expected to diminish with increasing depth, vulnerability of the sub-weathering zone being second only to the weathering layer itself.

4.2 The Topographic Effect. Velocity alteration by ground water activity appears to be the principal cause of the so-called topographic effect,* namely, the observation in many areas that seismic structural maps conform in some degree to the relief of the surface topography even though actual structural conformity does not exist.

An alternate explanation for the topographic effect is that it is due to overburden, higher velocity to a reflecting horizon occurring at a topographic high because of increased overburden thickness. The effect of overburden on velocity is probably more limited than implied in some publications. For example, in his very interesting and valuable paper, Dr. L. Y. Faust† derives the following empirical relation from a large mass of data:

$$v = 125.3(TZ)^{1/6}, \tag{6}$$

where v is the (instantaneous) velocity in ft/sec, T is geologic age in years and Z is depth in feet. This result is limited to some extent on the grounds that, since a wide variety of lithologic conditions, presumably other than lime, was used in combination, the effect of depth was not distinguished from lithologic variations basinward. For the data presented, higher velocity with greater depth may actually be associated either with greater overburden or with the fact that greater depth usually meant a depositional environment at a point farther basinward. Since lithologic variations basinward are expected to be usually identified with increasing velocity, the rate of increase of velocity with depth indicated by Eq. (6) is probably excessive in so far as overburden as such is concerned.

If the topographic effect is due to overburden alone, successively deeper seismic horizons should exhibit a successively different representation of surface topography, roughly in accordance with the theoretical diffusion factor.‡ On the

* M. B. Widess, "Effect of Surface Topography on Seismic Mapping," *Geophysics*, Vol. XI (July 1946), 362–372.

† "Seismic Velocity as a Function of Depth and Geologic Time," *Geophysics*, Vol. XVI (April 1951), 192–206.

‡ M. B. Widess, loc. cit., p. 366.

other hand, if the topographic effect is due to shallow lateral velocity variation associated for example with ground water action, the topographic effect in terms of reflection time should remain essentially the same for all horizons below the shallow level. Usually the latter of the two conditions is observed, thereby minimizing the overburden theory. Other evidence may also be cited. The topographic effect usually appears in a complex and seemingly contradictory form. The seismic maps may represent some topographic features in the area and not others, or else one side of a topographic feature may be represented while the other side is not. In some areas, depressed topographic features, such as river courses, are much more strongly represented than elevated features. This evidence indicates that the topographic effect cannot be adequately explained by the overburden theory, and therefore must be explained by other mechanisms for the lateral velocity variation. (A topographic effect can, of course, also result when a wrong subweathering velocity is used in computation, even when no lateral change of velocity occurs.) Lateral variation in velocity can be due to alluvial deposits lying unconformably on bed rock as well as to velocity alteration by ground water.

Short of seismic velocity measurements, it is at present very difficult to determine where and to what degree velocity alteration by ground water takes place. Velocity survey holes may have to be drilled to considerable depth in order to test for the presence of rapid lateral velocity variations. The customary drilling of velocity holes to 200 or 300 feet may fall far short of the depth necessary to meet the objective. On the whole, the field of ground water hydrology, the related chemistry of leaching and mineralization, and the consequent velocity alteration, is a field which needs considerably more clarification for exploration geophysicists than it has had in the past.

GEOPHYSICAL METHODS ADAPTED TO HIGHWAY ENGINEERING PROBLEMS*

R. WOODWARD MOORE†

ABSTRACT

Of the several geophysical methods used in exploration for oil and useful ore bodies, the earth-resistivity and seismic-refraction tests have been found to be the most adaptable to the shallow tests generally required in highway construction work. Of these, the earth-resistivity test is the faster and has a wider range of application to highway problems than does the seismic test. Use of both methods of tests in subsurface explorations for engineering structures is expanding.

The paper cites a growing need for a more thorough subsurface investigation of all engineering structure sites and gives examples of field data obtained by the Bureau of Public Roads when making preliminary geophysical surveys of proposed highway locations or structure sites.

The economic aspects and the advantages and limitations of the two methods of test are discussed with particular reference to their application to highway engineering problems.

Geophysical methods of exploring the subsurface have been applied to civil engineering projects for many years (3)[1]. Their use in connection with highway construction was reported on as early as 1933 (5, 9, 10). Recognizing the potential value of such rapid methods of exploring the subsurface, the Bureau of Public Roads began a program of research in 1933 for the purpose of fully evaluating their worth to the highway engineer. This study has continued up to the present time.

After a careful consideration of the several geophysical methods used in explorations for oil and valuable minerals, two methods of test were selected for detailed study and adaptation to the relatively shallow explorations required in highway work. These were the seismic refraction and earth-resistivity tests.

The magnetic and gravitational methods are dependent upon reactions caused by the subsurface formations that are spontaneous and have no easily defined relation with the depths from which they are recorded. Because of the difficulties inherent in interpreting the data obtained, their use in explorations of the shallow subsurface formations ordinarily associated with highway construction and other civil engineering works would be of questionable value.

Both of the methods selected for detailed study by the Bureau of Public Roads depend upon energy applied at the ground surface to produce measurable reactions within the subsurface formations. The operator has a certain measure of control over the depths from which these reactions are recorded. Test data are obtained with transmission and reception points separated by a very short dis-

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[1] Numbers in parentheses refer to references given in the bibliography.

tance initially and for a succession of gradually increased distances subsequently. This change in separation distance may be correlated with formation changes occurring at some depth below the ground surface. Both methods of test have been given a thorough trial on many of the problems commonly of concern to the roadbuilder and they have been found to have a very practical application in the field of highway engineering.

USE OF GEOPHYSICAL TESTS EXPANDING

Three States, Minnesota, Missouri and Wisconsin, made use of the earth-resistivity test in some measure prior to 1933 (5, 9, 10, 15). During the intervening years demonstration tests and full scale field tests, carried out by the Physical Research Branch of the Bureau of Public Roads in twenty-four of the forty-eight States and in the District of Columbia, have aroused an increased interest in the use of both seismic and resistivity methods of test. Eleven State highway departments have made use of one or the other of these methods of test in their subsurface exploration work. Three other State highway departments are planning to use the earth-resistivity test in the immediate future. Two additional States have expressed an interest in an early demonstration of the geophysical tests on problems typical of those encountered in their subsurface investigations.

The seismic test has been used by the Corps of Engineers, Department of the Army, since 1938 as a means for obtaining preliminary subsurface data useful in selecting dam sites for flood control purposes and their work has been reported on in some detail in the published literature (25, 27, 31, 33, 40, 43). This agency has also made use of the earth-resistivity test in studies of foundations for levees and for locating supplies of sand and gravel needed in construction work (29, 32, 40, 42).

The Geological Survey, the Bureau of Mines, and the Bureau of Reclamation, all of the Department of the Interior, are using both methods of test in their respective fields of activity (6, 17, 20, 23, 24, 30).

The resistivity test was used with good results in a systematic study of over 160 miles of the new extensions to the Pennsylvania Turnpike (48). Its use by one of the consulting firms connected with the New Jersey Turnpike is now getting underway.

Engineers visiting this country from all over the world to study our methods of building highways and other civil engineering structures have shown much interest in the possible use of the geophysical tests in their own countries. Some work has been done with the resistivity method of test on highway construction projects and other engineering works in Canada, England, and India. This test has also been used in a study of water supply problems in this country, in Europe and in Africa. The author has had a very limited experience in such work, however, and can only refer the reader to the partial list of references given in the bibliography attached to this report (17, 20, 21, 22, 24, 38, 41.)

GEOPHYSICAL TESTS APPLICABLE TO MANY HIGHWAY ENGINEERING PROBLEMS

The fundamental principles underlying the seismic and resistivity methods of test have been thoroughly described in the published literature and it is appropriate to confine this paper to a discussion of their various applications in highway construction work without discussion of their theoretical aspects. Both methods have proved of value in preliminary investigations of highway grading projects to obtain data for use both in the classification of excavation materials and in slope design for cut and fill sections. They have produced equally good results in investigations of solid rock formations such as are of importance in foundation studies for bridges or large buildings or in connection with proposed tunneling operations.

The earth-resistivity test has been used very successfully in locating isolated deposits of construction materials such as sand, gravel, quarry material and in some cases, special soils for use in road construction work (9, 10, 15, 35, 45, 47). This test has also been used with success in determining the depth of peat bogs and other swampy areas (9, 10, 47). Resistivity surveys have been applied to investigations of existing and potential landslide areas so troublesome in some sections of the country. There is need, however, for more detailed study of this vexing problem before drawing any conclusion regarding the usefulness of the resistivity test in such work.

INCREASING NEED FOR THOROUGH SUBSURFACE EXPLORATIONS OF ENGINEERING STRUCTURE SITES

Troublesome, unexpected subsurface conditions encountered in engineering construction work in the past have indicated the need for thorough exploration of the subsurface to disclose conditions likely to aid or hinder a given construction program. In road construction, for example, much has been learned regarding the stability, bearing power, etc., of various soils that constitute the subgrade. On the more plastic soils a layer of granular material, 10 to 12 inches thick, may be required to improve the stability.

Cut slopes and embankment slopes must be designed with due regard for the material involved, that is, flat-lying for some soils and with steeper slopes for the more stable soils and weathered rock formations. Obviously greater quantities of materials must be excavated to provide the flat slopes and higher construction costs are a result. Subsurface exploration work will often provide data useful in achieving an accurate and optimum design of slope.

Poor subgrade conditions may be improved or, at times, avoided by a simple and practical change in the grade line to place the road bed above or below a subsurface layer known to be troublesome. Many sections of roadway have, no doubt, been constructed with the pavement resting upon soils contributing to its failure when relatively good soils existed at only slightly greater depths. The resistivity test can be used to determine the thickness of a plastic clay for-

mation or obtain the depth of overburden to a stratum of granular soils that may be used in stabilizing the poor quality clay soils.

For example, engineering estimates of the cost of a proposed roadway were prepared on the basis that large quantities of borrow material of a granular type would be needed for topping material over unsuitable clay soils. Actually much of the needed granular material was present within the proposed cut sections but hidden beneath a screen of surface soils and its use, in lieu of the rather expensive borrow material, made possible a considerable reduction in the estimated cost.

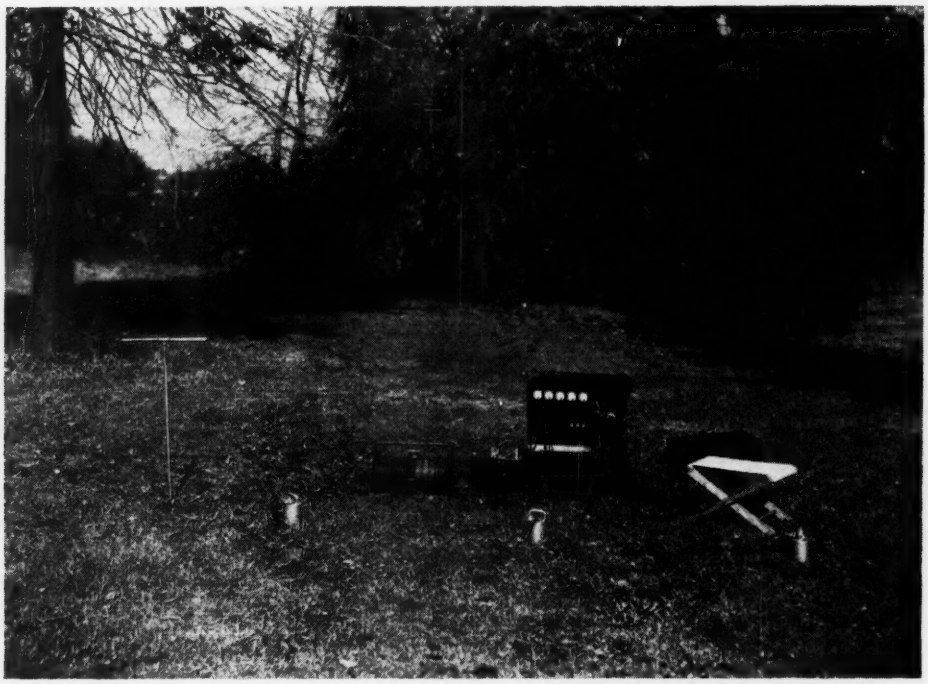


FIG. 1. Refraction seismograph developed by the Bureau of Public Roads for use in shallow subsurface explorations.

Bridge piers have been designed for solid rock foundations when no rock existed at the depths shown on the plans. Highway grading projects have been designed for rock slopes when earth conditions existed over much of the right-of-way. As a result bid prices for excavation were much higher than they would have been if a design for earth slopes had been a part of the plans furnished those bidding on the project. Obviously, any rapid and inexpensive means of exploring the subsurface, such as the two geophysical tests under discussion, can be of great value by adding detailed information regarding the subsurface formations and thus be helpful in avoiding the situations just described.

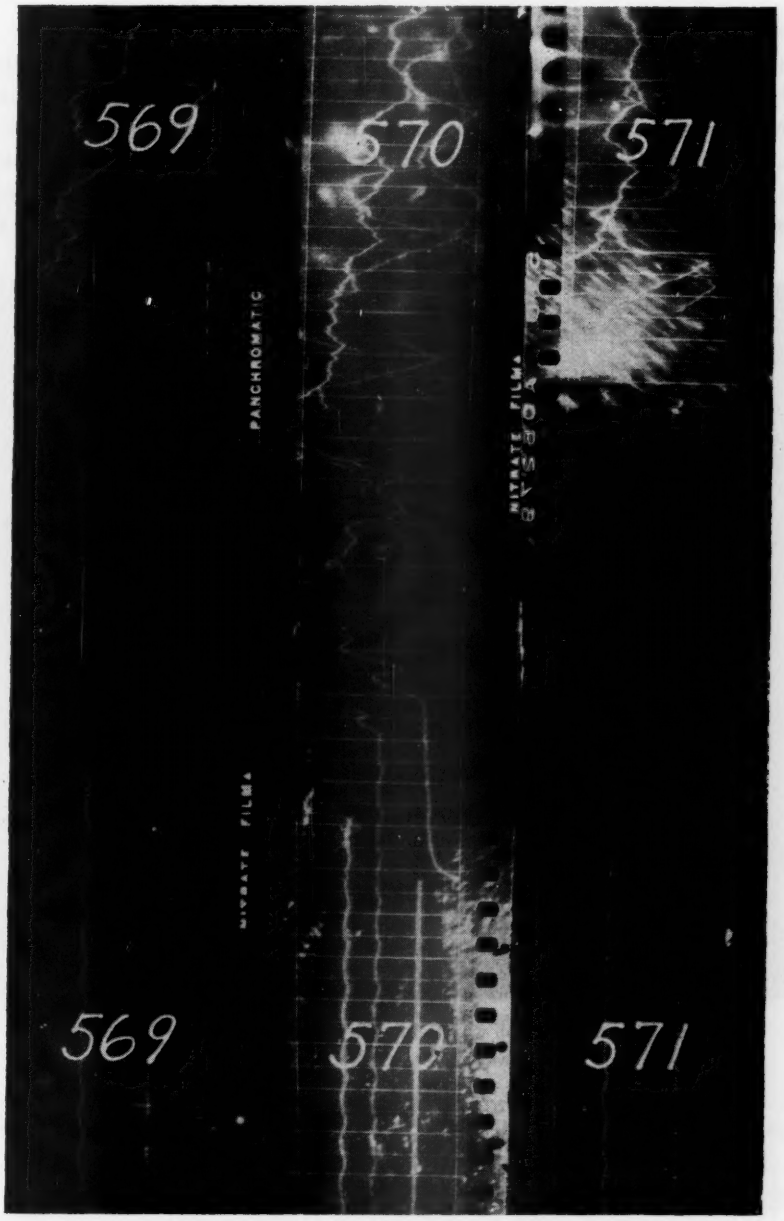


FIG. 2. Typical film records obtained in seismic tests. Note the "kick" displacement on the right hand trace.

PORTABILITY ESSENTIAL IN EQUIPMENT FOR USE IN RECONNAISSANCE SURVEYS OF NEW HIGHWAY LOCATIONS

Much of the highway construction done by the Bureau of Public Roads is in rugged terrain of the National Park and National Forest areas throughout the country. New locations of proposed roadways are often far removed from existing roads and trails and equipment that is readily portable is required for the preliminary surveys to obtain subsurface data needed in designing the proposed roadway. Figure 1 shows the portable seismic equipment developed by the Physi-

FIG. 3. Seismic party on way to investigate a tunnel on the Blue Ridge Parkway in western North Carolina.

cal Research Branch of the Bureau of Public Roads for shallow seismic refraction work. This apparatus, designed in 1934 prior to much of the development of the rugged electronic equipment and the small but sensitive galvanometers now available was designed without amplification of the seismic impulses, using simple microphonic, carbon-button type detectors (shown in the foreground). This is a 3-channel unit using conventional 35 mm film in the recording camera. Timing lines are placed on the film by means of an electrically driven tuning fork operating at 100 cycles per second and equipped to permit 200 flashes of light

to reach the recording film each second. Figure 2 shows several seismic records typical of those obtained with this apparatus. As stated, the space between the timing lines corresponds to a time interval of 0.005 second.

The shot instant, shown by the break in the right-hand trace on each of the records in Figure 2, is obtained by a circuit, separate from the shot circuit, that includes a small wire wrapped around the explosive and carrying a few milliamperes of current. The rupture of this wire causes the break in the trace as shown. The rupture of the bridge-wire of the electric detonator used to explode

FIG. 4. Milliammeter-potentiometer type of resistivity apparatus used by the Bureau of Public Roads.

the charge is also used to obtain the shot instant in cases where long shots are required, beyond the reach of the four-wire cable carried on the shot-line reel.

The results obtained with this apparatus during the past 16 years have been very satisfactory, both in the work done by the Bureau of Public Roads and that carried on by other Federal agencies. Recently, however, other portable seismic equipment has been described (46) which makes use of electromagnetic detectors, twelve in number, and employs electronic amplification in the detector circuits. This improved apparatus should be beneficial in stimulating the use of the seismic test on shallow exploration work for engineering structures.

Figure 3 shows how the apparatus shown in Figure 1 is transported over rough mountain locations in explorations of proposed tunnel sites, classification of excavation materials, and other highway problems.

Portability was a prerequisite, also, in the design of the simple milliammeter-potentiometer type of resistivity apparatus used by the Bureau of Public Roads and shown in Figure 4. A party of four men can carry this apparatus over any terrain and make rapid tests to determine the character of the subsurface materials existing throughout a proposed construction project.

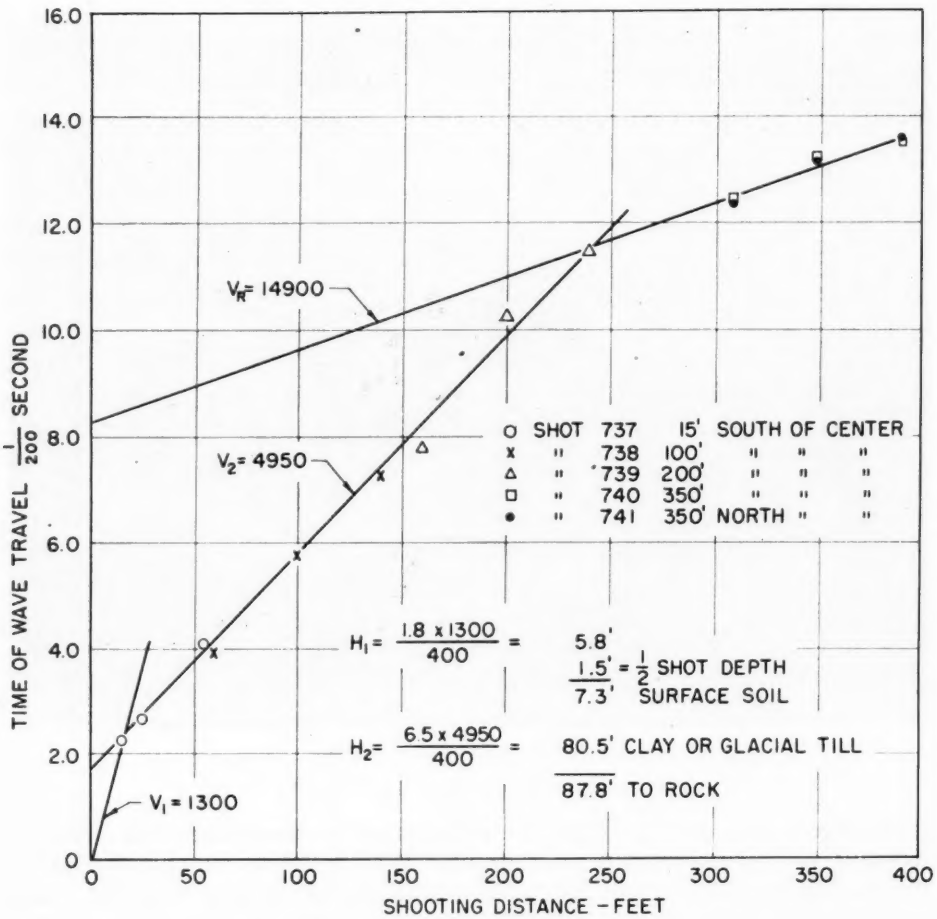


FIG. 5. Time-distance graph for seismic tests at a proposed dam in New England.

RESULTS OBTAINED WITH THE SEISMOGRAPH DESCRIBED

The seismic refraction test depends upon the existence of differences in the velocity of wave transmission between the various materials constituting the

earth's crust and makes use of these for their location and identification. Velocities as low as 600 feet per second have been found in loose surface soils. Clay soils with no high degree of compaction may have velocities ranging from 2,000 to 3,500 feet per second. More dense clays, shales, cemented gravels, water-logged silts, and weathered or badly fractured rock usually show wave velocities within the range 4,000 to 8,000 or 9,000 feet per second. Velocities ranging from 10,000 to 20,000 feet per second have been recorded for various solid rock formations.

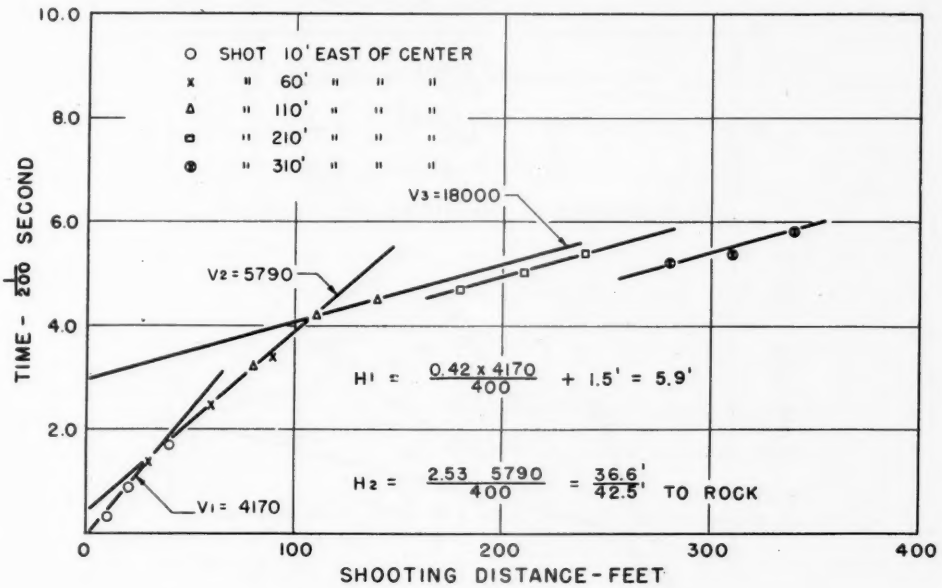


FIG. 6. Time-distance graph for seismic text at toll bridge location, Hampton, New Hampshire.

The dense, hard rock formations are easily and accurately located beneath a loose soil overburden. It is usually possible to locate such material beneath the materials of intermediate velocity as well. Trouble may be experienced, however, in attempts to identify the intermediate velocity materials without some knowledge of the local geologic conditions.

The conventional time-distance graphs familiar to those concerned with seismic refraction work are used in computing the depths to an underground rock surface. Figure 5 shows such a graph typical of those prepared from data obtained in seismic refraction tests in New England. This particular test was one of those made while demonstrating the seismic method to the Corps of Engineers, Department of the Army, prior to the adoption of the test by that agency as standard procedure in much of their exploration work.

The simple formulas shown in the computations on the graph utilize the intercepts on the time axis and the wave velocities in the respective soil layers as

computed from the reciprocals of the slopes of the straight-line portions of the graph. In the relatively shallow explorations usually encountered in highway construction there is seldom a need for using the more exact formulas required for the deeper tests and in instances where the geologic formation under investigation consists of adjacent layers having only slightly differing velocity characteristics. Calibration or trial tests made over geologic formations exposed in roadway cuts, or proved by other means, in the area being explored are necessary for the final analysis of the data obtained in the exploration tests made in the area.

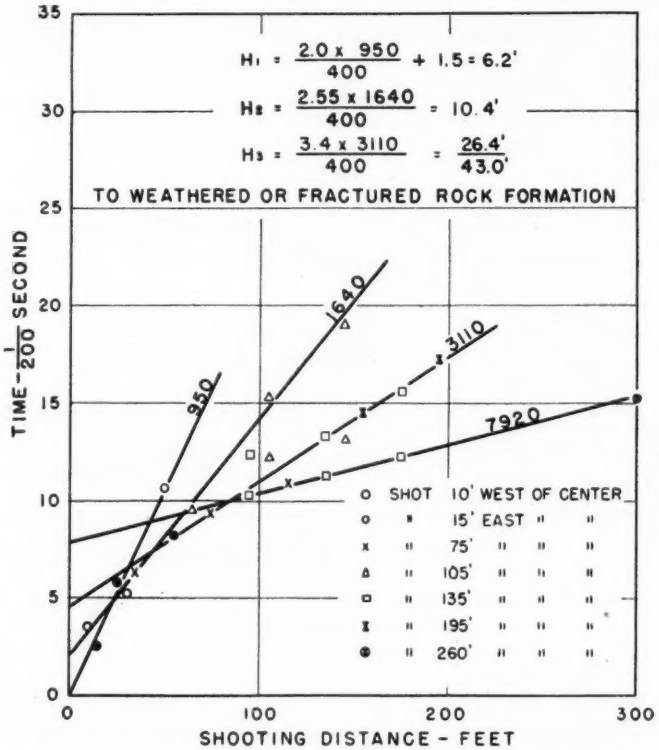

$H_1 = \frac{2.0 \times 950}{400} + 1.5 = 6.2'$
$H_2 = \frac{2.55 \times 1640}{400} = 10.4'$
$H_3 = \frac{3.4 \times 3110}{400} = \frac{26.4'}{43.0'}$
TO WEATHERED OR FRACTURED ROCK FORMATION
TIME - $\frac{1}{200}$ SECOND
SHOOTING DISTANCE - FEET
950
1640
3110
7920
SHOT 10' WEST OF CENTER
" 15' EAST " "
" 75' " "
" 105' " "
" 135' " "
" 195' " "
" 260' " "

FIG. 7. Seismic data obtained at proposed location of Tunnel No. 3, Project 2Z2, Blue Ridge Parkway, in western North Carolina.

Foundation Exploration.—The time-distance graph for a seismic test made at a proposed bridge site at Hampton, New Hampshire, is shown in Figure 6. For this test the detectors were placed on a line, spaced 30 feet apart, and five shots were fired at various distances from the detectors on the detector line extended. The detectors were placed directly on the ground surface and the explosive was buried 3 or 4 feet below the surface, using a soil auger to bore the holes. In this instance, the detectors and shot points were located along the water's edge and the relatively high wave velocities obtained initially were the result of

the water-logged condition of the near-surface soils. Apparently, the bedrock is at shallower depths at the locations of the last two shots placed 210 feet and 310 feet from the center of the detector spread. The total depth to bedrock, 42.5 feet, includes a correction of 1.5 feet to allow for one-half the shot depth.

Investigation of Tunnel Sites.—Figure 7 contains a time-distance graph for a seismic test made while investigating one of five proposed tunnel locations on a

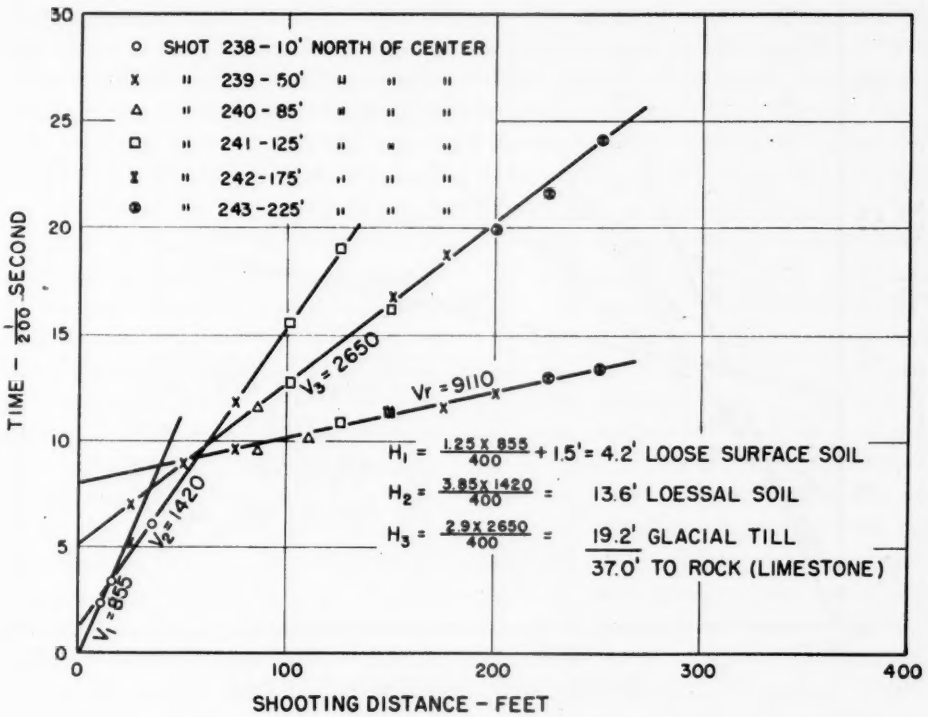

SHOT 238 - 10' NORTH OF CENTER
" 239 - 50' " " "
" 240 - 85' " " "
" 241 - 125' " " "
" 242 - 175' " " "
" 243 - 225' " " "
TIME - 1/200 SECOND
SHOOTING DISTANCE - FEET
V1 = 865
V2 = 1420
V3 = 2650
Vr = 9110
H1 = 1.25 X 855 / 400 + 1.5' = 4.2' LOOSE SURFACE SOIL
H2 = 3.85 X 1420 / 400 = 13.6' LOESSAL SOIL
H3 = 2.9 X 2650 / 400 = 19.2' GLACIAL TILL
37.0' TO ROCK (LIMESTONE)

FIG. 8. Time-distance graph for seismic test made near Council Bluffs, Iowa, in a search for quarry material.

five-mile-long section of the Blue Ridge Parkway under construction in the Great Smoky Mountains National Park in Western North Carolina. The relatively low velocity (7,920 feet per second) obtained for the material lying below a depth of 43.0 feet is indicative of weathered or badly broken rock, neither of which is a satisfactory formation through which to drive a tunnel.

Location of Quarry Material.—In certain sections of the country, rock outcrops are infrequent and quarry sites must be located and explored by surface geology and bore holes or test pits. Figure 8 illustrates how the relatively inexpensive seismic test can be used to locate suitable rock formations at some depth below the surface. This graph also illustrates how the "secondary events" on the

film records may be used to establish the existence of relatively thin formation layers not disclosed in the normal plotting of the first arrivals. The computed overall depth at this location would be in error some 8 or 9 feet if the third layer (2,650 feet per second) had not been taken into consideration.

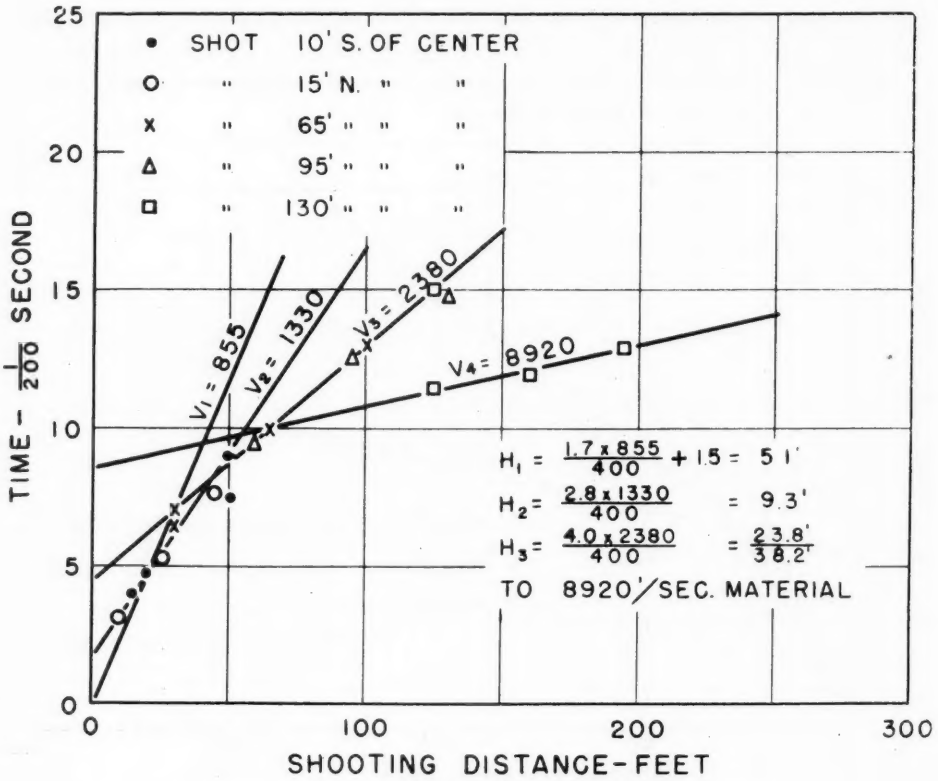


FIG. 9. Time-distance graph for seismic test made at Station 36+00, Project 2Y4, Blue Ridge Parkway, in western North Carolina.

Slope Design and Earthwork Classification.—In Figure 9 seismic data are shown for a test made while investigating another section of the Blue Ridge Parkway. This test showed weathered granite, easily excavated by heavy earth-moving equipment, present to a depth of 38 feet, or some 20 feet below the proposed grade line. Solid rock, somewhat fractured and jointed, is indicated at greater depth.

Hand-bored auger holes, often used in the soils surveys made in such areas, are difficult to force down through such weathered rock and their cost mounts with any appreciable footage through such materials.

Many other examples could be given to illustrate the successful application of seismic tests to various highway engineering problems throughout the country.

However, in order to include a discussion of the earth-resistivity test and its important application to a variety of problems met with in highway engineering work in this rather short paper, it is necessary to curtail the discussion of the seismic method.

RESULTS OBTAINED WITH THE EARTH-RESISTIVITY TEST

The earth-resistivity method of exploring the subsurface has been used on engineering projects for more than 20 years (3). Its application to problems of highway construction has been expanded in recent years. In this method of test measurements are made of the resistance of the earth's materials to the passage of an electric current and from the data predictions are made regarding the location and the character of the materials involved. High resistance is usually associated with sand, gravel, dry, loose surface soils, and solid rock. Much lower resistances are usually found in the moist clays, silts, and mucky, organic soils. The current flow that is measured is electrolytic in nature in that it is dependent upon the moisture and dissolved salts within a material to provide a path for the current. The measured resistivity is usually expressed as ohms per centimeter cube or ohm-centimeters. Within a relatively restricted area, a given resistivity value may have definite geological significance, but may lose its significance when attempts are made to apply it to materials in some other region. As an example, materials easily removed by heavy earth-moving equipment have been found with resistivities as high as 1,500,000 ohm-centimeters, in one locality, while, in contrast, solid rock, requiring blasting for removal, has been found to have resistivity values as low as 5,000 to 10,000 ohm-centimeters in another part of the country. Trial or calibration tests are essential in each locality where a resistivity survey is to be made. Such tests, made over each type of soil, rock or other formation in the area, produce characteristic curves, showing the relation of resistivity to depth of test. These calibration curves serve as a basis of comparison for the field curves obtained in carrying out a resistivity survey in the area. Similar geologic conditions are indicated whenever a field curve closely resembles a particular calibration curve.

As mentioned earlier, the theoretical aspects of the resistivity method of test have been adequately described by various authors and there is no need for discussion of theory in this paper. In the work done by the Bureau of Public Roads the Wenner (1) 4-electrode configuration is used and the simple empirical relations assumed by Gish and Rooney (2) and others have been made the basis for a relatively simple empirical method of analysis of the resistivity-depth curves. This method, termed the cumulative curve method, has been described in earlier publications (34, 36, 37, 45, 47). It has been used with very satisfactory results during the past 10 or 12 years.

The curves in Figure 10 are illustrative of the cumulative curve method of analysis. Curve A was prepared from field data obtained for a two-layer formation, clay underlain by rock, and the ordinates are plotted to the "individual

value" scale. Curve B shows the same field data plotted to the "cumulative" scale. Curve A indicates the probable number of subsurface strata, the inflection in the curve being used in the analysis to give significance to the intersection of straight lines as obtained in the cumulative curve (curve B). The presence of the underlying rock is indicated by the trend in curve A at an electrode spacing of 7.5 to 9.0 feet, while the actual depth to the rock is estimated to be 13.0 feet from the intersection of the two straight lines in curve B. Very minor trends in curve A

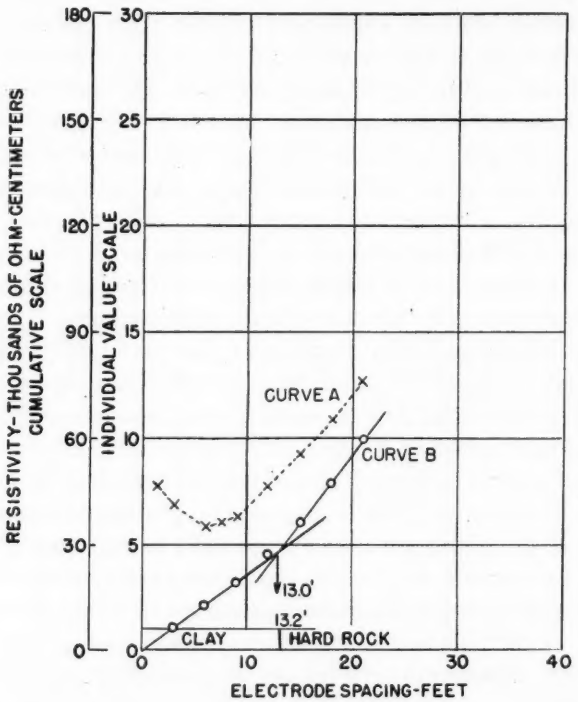


FIG. 10. Empirical method of analysis applied to resistivity curve for a clay stratum under-lain by rock in the vicinity of Washington, D. C.

are used in this manner to give validity to the intersections obtained in the cumulative curve. The data used in plotting the curves of Figure 10 are given in Table 1.

Although theoretical methods of analysis, based upon ideal conditions not commonly found in nature, have been used with success by various investigators, the author has found them to be of limited value in the shallow explorations associated with highway work. For the most part, they involve the use of curves or groups of curves, plotted from data computed for several assumed layer thicknesses and resistivities, to which the field curves are fitted in an effort to determine which of the assumed conditions most nearly approaches those existing at the test location. These methods of analysis are time-consuming and appear

to be more practical for the deeper tests than they are for shallow work. A review of the references given in the appended bibliography should be made for a thorough study of such methods of analysis (4, 6, 7, 14, 26, 28, 30).

Resistivity Test Applied to Slope Design.—Figure 11 shows data from a resistivity-depth test made at the same location as that of the seismic test referred to in Figure 9. The change in the subsurface strata indicated at a depth of 37.6 feet checks closely with the depth of 38.2 feet to the high velocity stratum located by the seismograph. The first part of the curve closely resembles several calibration curves obtained over weathered granite formations in that locality.

TABLE 1

RESISTIVITY-DEPTH TEST DATA USED IN FIGURE 10

Electrode spacing	Apparent resistivity	Cumulative resistivity	Remarks
Feet	Ohm-centimeters	Ohm-centimeters	
3	6,885	6,885	Drill hole record showed clay to 13.2 feet underlain by hard rock.
6	5,990	12,875	
9	6,325	19,200	
12	7,735	26,935	
15	9,260	36,195	
18	10,925	47,120	
21	12,730	59,850	
1.5	7,955		Not used in cumulative curve.
7.5	6,045		Not used in cumulative curve.

In instances where seismic and resistivity data produce such closely comparable indications there is little need for further direct exploratory work with a drill. On this particular project, $3\frac{1}{2}$ miles of rough mountain location were explored in four working days. Thirty-one cuts, with depths ranging from 10 feet to 43 feet at the centerline, were investigated with an average rate of $2\frac{1}{2}$ tests per hour, each test being carried down to a depth of 60 feet. This project is now under construction and the materials found thus far have been substantially as predicted from the resistivity survey.

In many instances the resistivity curves obtained over solid rock and over typical earth formations in a given area differ so markedly in shape and trend that visual inspection is all that is required to determine the character of the materials to the depth of the proposed grade line or even to the full depth of test. Figure 12 contains calibration curves from tests made over earth and over solid rock in an area near Farmington, in southeast Missouri. Since curves obtained over several miles of a proposed grading project in this area were all of the low value, flat lying type, they could only be interpreted as indicating earth excavation above the grade line and this interpretation required only visual examination.

Foundation Problems Studied.—There have been instances where bridge piers designed for solid rock foundations have had to be placed upon piling or have been

extended to appreciably greater depths at considerable additional cost because of inadequate or erroneous information regarding bedrock elevations. The geophysical tests, used in conjunction with direct means of exploring the subsurface, can be of considerable assistance in providing more complete and dependable data regarding the subsurface formations. Figure 13 shows resistivity data for three tests made in a post-construction survey of a bridge site in southwest

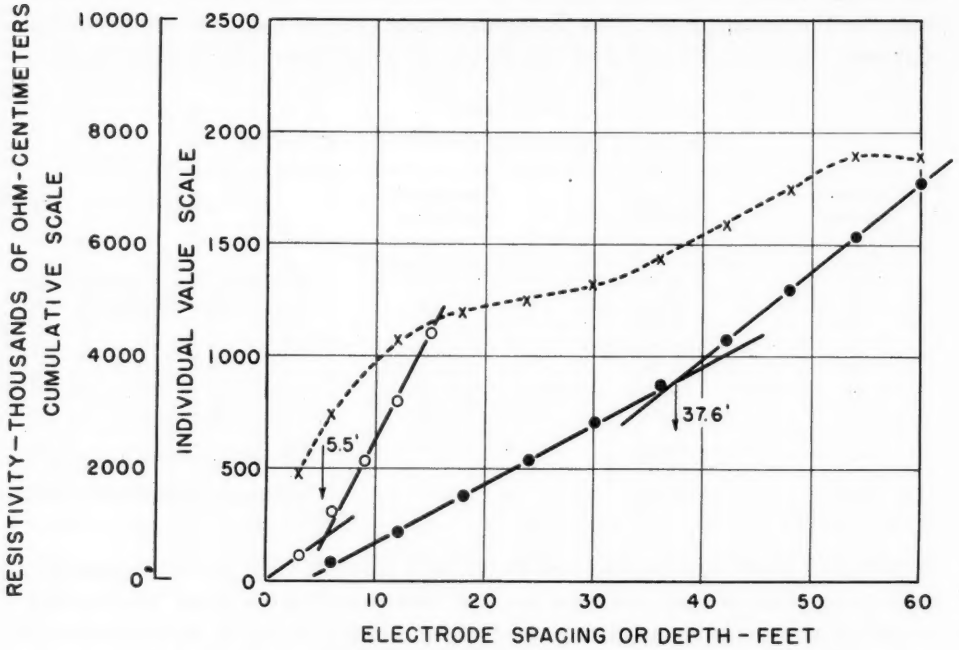


FIG. 11. Earth resistivity test discloses presence of granite rock beneath weathered granite, Station 36+00, Project 2Y4, Blue Ridge Parkway.

Georgia. In this figure the indications of the resistivity tests are compared with the rock surface depths as shown on the plans, and as found during construction. It is apparent that the information provided by the geophysical test was more accurate than that obtained with the drill. Since these tests can be made in a period of 15–20 minutes, their possibilities for use in rapid preliminary surveys can be fully appreciated.

Resistivity Tests Effective at Tunnel Sites.—It is possible to calibrate the resistivity test over exposures of material known to be satisfactory for tunnel work and over other materials having less satisfactory characteristics and thus obtain resistivity curves which may be used to evaluate the data from tests made at a proposed tunnel location elsewhere in the same general locality. Referring to Figure 14, curve No. 1 was obtained over a solid rock cut on a partially graded section of the Blue Ridge Parkway previously referred to. The material was

considered suitable for tunneling purposes. Curves Nos. 2 and 3 show data from tests made over a nearby ridge composed of weathered rock. Originally a tunnel had been planned to carry the roadway through this hill. Following the collapse of the tunnel workings a short time after construction work was begun, a redesign for an open cut was required. Curve No. 4 was obtained at the location of one of five tunnels planned for an adjoining 5-mile section of the Parkway. Since its

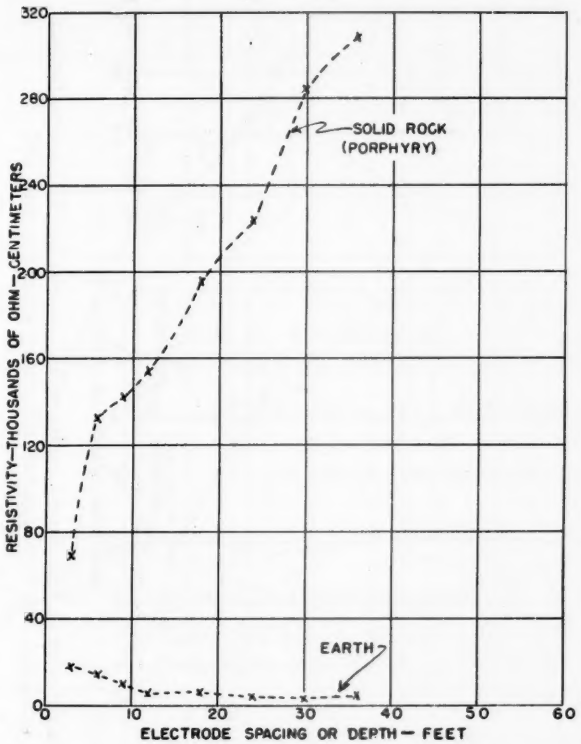


FIG. 12. Typical resistivity calibration curves over solid rock and earth formations near Farmington, Missouri.

closely resembles curves 2 and 3, it was interpreted as indicating that unsatisfactory material for tunneling existed at this location also. The seismic data in Figure 7 were obtained at this same location. These data also showed no indication of the hard rock desirable for tunnel construction. Only four days were required to explore the five tunnel sites and about 3 miles of intervening grading on the project.

Resistivity Test Useful in Prospecting for Construction Materials.—The supplies of sand, gravel, and suitable quarry materials so plentiful in some areas are being depleted to dangerously low levels elsewhere in the country. The resistivity test is especially useful in a search for such materials. It is possible

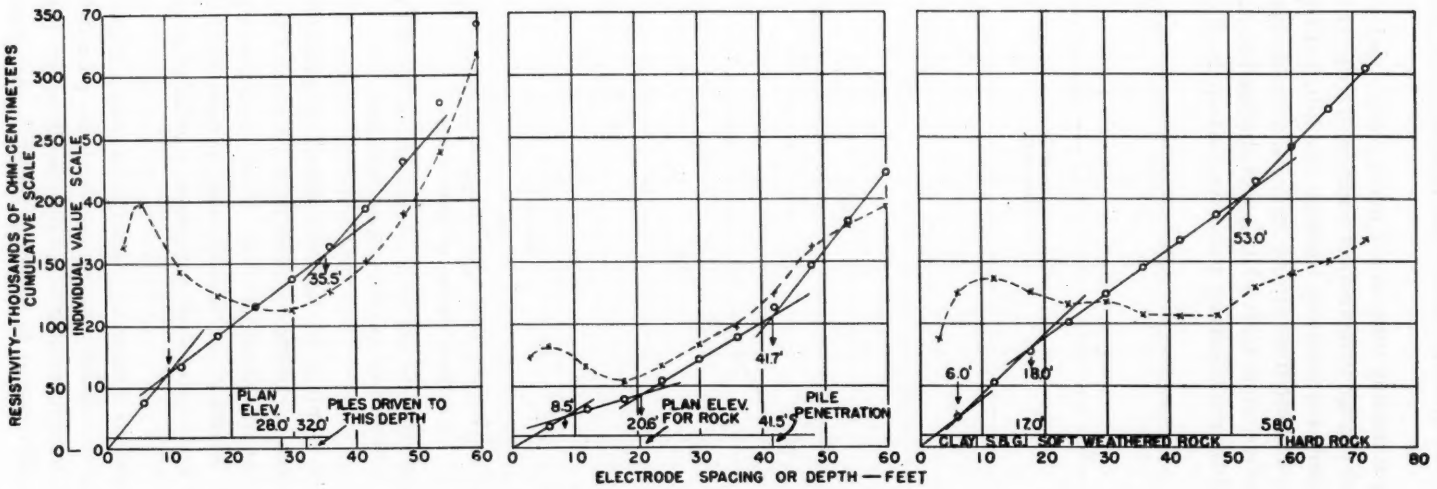


FIG. 13. Earth resistivity tests at Flint River Crossing on U.S. 19, south of Thomaston, Georgia, locate subsurface rock for bridge foundation more accurately than drill.

to make a constant-depth resistivity traverse along a random line over an area and locate any appreciable quantities of granular materials or rock that may be present within the depth being prospected. Figure 15 contains curves from several such traverses showing the effect of deposits of sand and gravel lying within 30 feet of the surface as indicated by the resistivity "highs" appearing in three of the curves, the nature of the material having been established by calibration

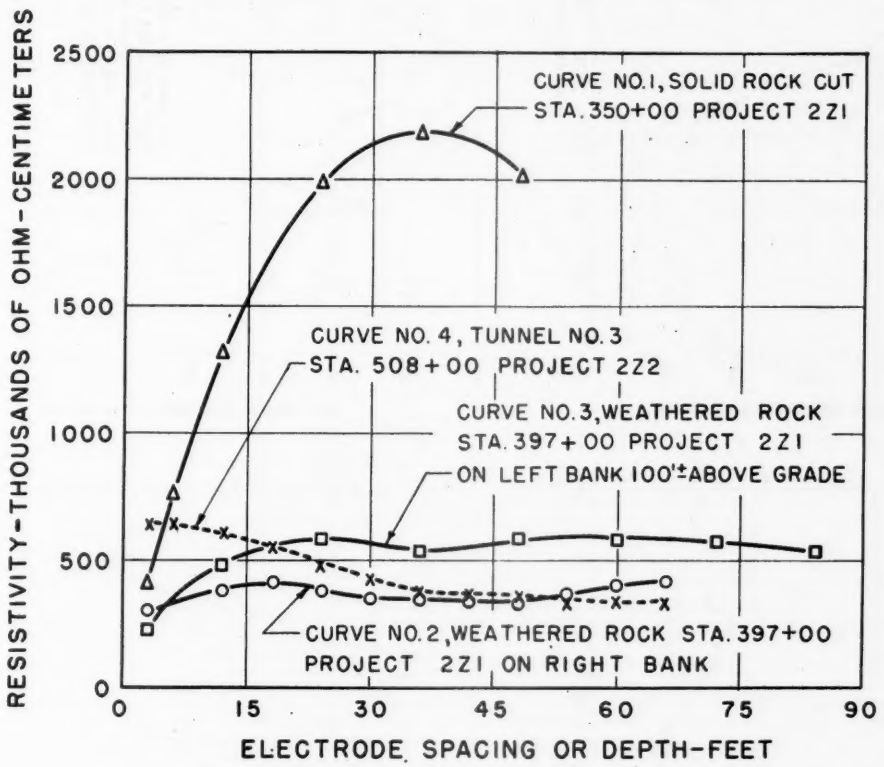
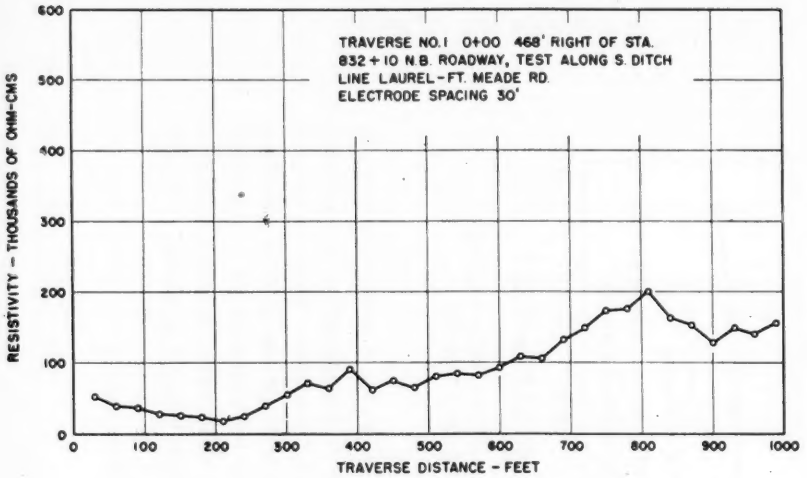
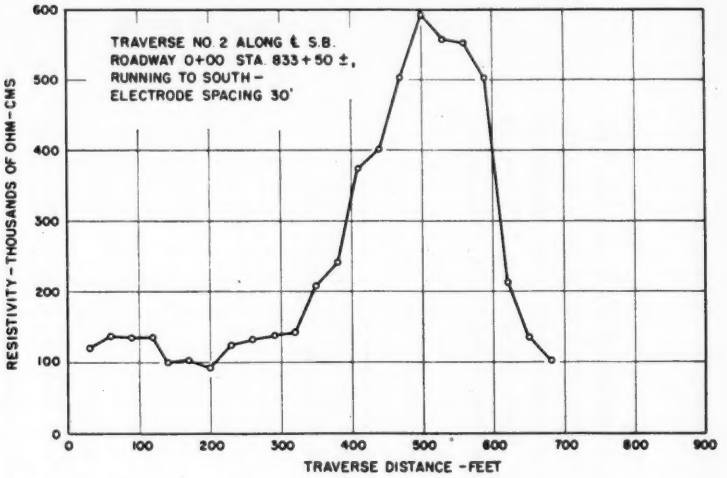
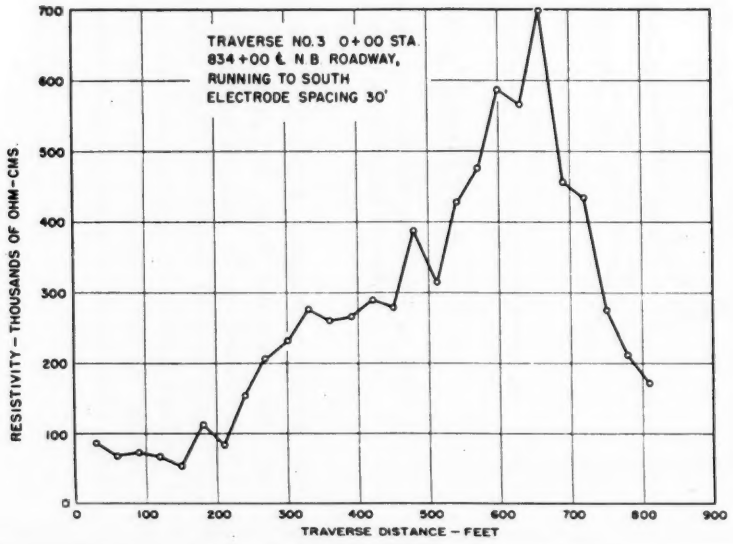


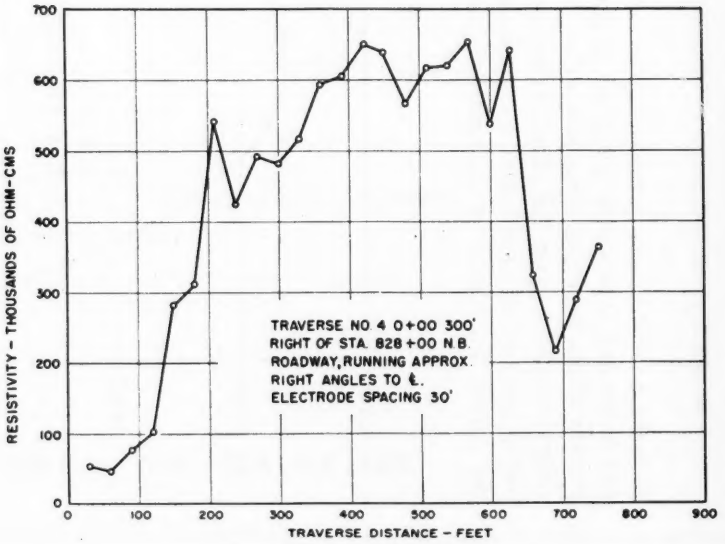
FIG. 14. Resistivity calibration curves (solid lines) and field curve obtained at location of Tunnel No. 3, Project 2Z2, Blue Ridge Parkway.

tests. From explorations of this type it is possible to plot a resistivity contour map such as the one shown in Figure 16. The zone of highest resistivity outlines an area containing the greatest amount of granular material. With deposits of this type a limited number of depth tests will determine the general thickness of the high resistivity materials and provide a basis for computing the quantities available. At the location where these particular data were obtained 80,000 to 90,000 cubic yards of good granular materials were located in about 13 hours.


TRAVERSE NO.1 0+00 468' RIGHT OF STA. 832+10 N.B. ROADWAY, TEST ALONG S. DITCH LINE LAUREL-FT. MEADE RD. ELECTRODE SPACING 30'
RESISTIVITY - THOUSANDS OF OHM-CMS
TRAVERSE DISTANCE - FEET


TRAVERSE NO 2 ALONG ℄ S.B. ROADWAY 0+00 STA. 833+50 ±, RUNNING TO SOUTH - ELECTRODE SPACING 30'
RESISTIVITY - THOUSANDS OF OHM-CMS
TRAVERSE DISTANCE - FEET


TRAVERSE NO.3 0+00 STA. 834+00 ℄ N.B. ROADWAY, RUNNING TO SOUTH ELECTRODE SPACING 30'
RESISTIVITY - THOUSANDS OF OHM-CMS.
TRAVERSE DISTANCE - FEET


TRAVERSE NO 4 0+00 300' RIGHT OF STA. 828+00 N.B. ROADWAY, RUNNING APPROX. RIGHT ANGLES TO ℄. ELECTRODE SPACING 30'
RESISTIVITY - THOUSANDS OF OHM-CMS
TRAVERSE DISTANCE - FEET

RELATIVE MERITS OF THE TWO GEOPHYSICAL TEST METHODS

The seismic test is well suited to a study of problems involving the location of bedrock beneath unconsolidated soils and materials of lesser density than that of the rock such as, for example, the classification of excavation materials and a determination of foundation conditions for large buildings, bridges, dams, etc. It is equally valuable in a study of proposed tunnel sites. In areas where the

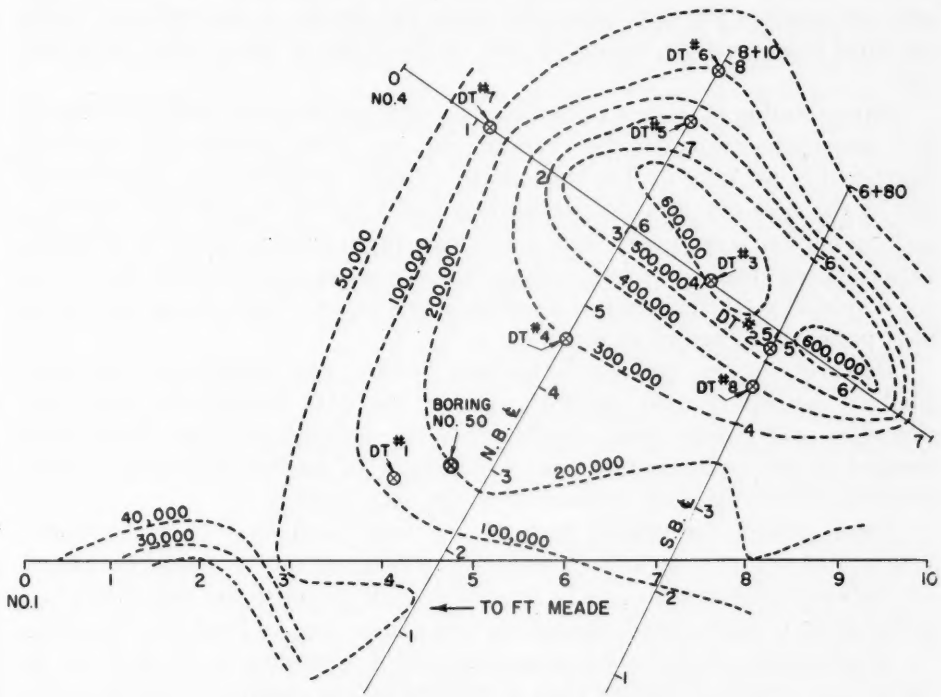


FIG. 16. Resistivity contour map outlines lateral extent of sand and gravel deposit, Baltimore-Washington Parkway.

geologic formation consists of alternating beds of shale and limestone or sandstone, it is not likely to be useful except to determine the depth of overburden to the first dense layer. The seismic waves in the lower-velocity shales would be masked by the effect of the first arrivals through the overlying layer of higher velocity rock.

In contrast, the earth-resistivity test can be used satisfactorily in either of the formations just described, locating the rock layers with some accuracy and also showing the change to the less dense formation as well,

The resistivity test is well adapted to a rapid survey of large areas in prospecting for the granular soils, gravels, and other materials valuable for highway construction work. Seismic tests, on the other hand, are of little value for such surveys, since the wave velocities associated with such materials are not readily

identified. The resistivity test method is better adapted than the seismic method to determination of conditions in swampy areas such as peat bogs and the marshy areas along the sea coast.

The seismic test is many times faster and much less expensive than any of the direct methods used in shallow subsurface explorations, but it is much slower than the resistivity test, particularly for explorations to the depths of 15 to 50 feet usually required in highway work. With one small party two to eight seismic tests are possible per day, depending upon the depths to be explored. Under the same conditions the resistivity test can be made at about three times this rate.

Interpretation of seismic refraction data obtained in areas where the subsurface formations are reasonably uniform and not badly upheaved or unevenly weathered is not difficult. The time-distance graphs of figures 5 to 9 are illustrative of the clear-cut, straight-line relation found for the time of wave travel in each formation layer under such conditions. Interpretation of earth-resistivity data from tests made over such geologic formations are equally simple when using the empirical methods mentioned earlier in this paper. This is borne out by the data presented in figures 10 to 16.

However, as the geologic formations become less homogenous and more jumbled in their relation one with another, the data obtained by either test procedure will require more careful study for a proper analysis. With either method of test, calibration or trial tests should be made over known geologic conditions for satisfactory evaluation of the data obtained.

Some geologic formations, such as dry, loose sand, may have resistivities comparable to that of an underlying rock in which case the location of the boundary between the materials may be impossible with the resistivity test. When such a formation is encountered, the seismic test can be used to locate the boundary.

Maintenance of the seismic apparatus and its operation in the field will require more extensive training than is required for the resistivity apparatus. The transportation, use, and storage of explosives at times constitutes a problem when using the seismic method.

One rather important advantage of the resistivity method over the seismic method is the constant-depth traverse procedure, which, with the resistivity method, makes it possible to locate abrupt irregularities in an underlying rock formation and to locate the lateral limits of subsurface formations. This traverse can be made at a rate of 4,000 to 5,000 feet per day and is particularly valuable in a reconnaissance survey to locate construction materials or in a detailed study for mapping the contours of a subsurface rock formation.

Stray currents emanating from ore bodies, cross-country pipe lines or other sources have been known to affect resistivity measurements adversely and special apparatus has been designed to mitigate the effect of such disturbances. It has been the author's experience, however, with tests made in many parts of the country, that the simple milliammeter-potentiometer type of apparatus without

these special features can be used effectively in the shallow tests with little likelihood of serious interference from this cause.

ECONOMIC ADVANTAGES OF THE GEOPHYSICAL TEST METHODS

Ordinary core borings can be ten to twenty times more costly than seismic tests, assuming that the boring equipment can be brought in on a given location. Resistivity tests, wherever they can be used, are even less costly than seismic tests.

At the present time bid prices for unclassified excavation on a roadway project may range from $0.30 to as high as $1.25 per cubic yard, depending in large part upon the difficulty which the bidder expects to experience in loosening and removing the formation predominating throughout the project. Excavation quantities for a two-lane roadway in mountainous regions may average 100,000 cubic yards per mile. This figure can easily reach 200,000 yards per mile for the four-lane divided highways being constructed today. Obviously, any information that can be furnished on the plans to show prospective bidders more definitely the nature of the material to be excavated will tend to improve the bid price. This is particularly true where the absence of rock excavation can be established.

Resistivity surveys of many miles of proposed roadway have been made at a rate in excess of a mile per day, and at a cost of about $100.00 per mile. This cost, plus the added expense of a relatively small number of test pits or hand-bored holes required to supply the calibration data for the geophysical survey, is very low in contrast to the savings possible from information obtained with a subsurface survey by geophysical methods.

Preliminary plans for a single 3-mile section of the Baltimore-Washington Parkway, now being constructed in Maryland, required a borrow item of approximately 90,000 cubic yards of select granular material for use as topping over the poor clay soils which constitute the subgrade over much of the project. An alternative was to attempt to locate adequate supplies of such materials along the roadway itself. As a result of a resistivity survey supplemented by several judiciously placed test pits, all of the granular materials in an amount sufficient for the project were found within the proposed roadway limits. Handled in the contract as ordinary excavation and with a small extra payment for distribution over the finished grade, the total unit bid price for the required materials was about $0.50 per yard. Bid prices for such materials classified as borrow items have ranged from $1.00 to $2.00 per yard elsewhere in the same general area. Thus an indicated savings of over $0.50 per yard resulted and a total savings in excess of $50,000 may have been achieved. One small party made the necessary field tests in about 13 hours' time.

Other, less evident, savings are effected by eliminating the troublesome and sometimes costly design and engineering changes required to accommodate construction to unforeseen subsurface conditions encountered as the work proceeds.

CONCLUSIONS

In conclusion, it should be emphasized that, despite the optimistic tone of the foregoing discussion, there will be some subsurface conditions for which either or both of the geophysical tests will have but limited application. This is true also of other and more conventional methods of exploring the subsurface. The earth-resistivity test is faster and has a wider application to most highway problems than does the seismic test. For this reason it is the present practice of the Bureau of Public Roads to use the resistivity method of test initially when making a survey and to use the seismic method (1) to obtain confirming data or (2) in areas where, for one reason or another, the resistivity test does not provide conclusive data. Both tests are best used in a preliminary or reconnaissance survey prior to any more detailed exploration by drill or test pit. Their use in conjunction with the current methods of direct exploration can result in a substantial savings in the cost of future explorations of the subsurface.

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MAGNETIC SUSCEPTIBILITY MEASUREMENTS IN MINNESOTA

PART I: TECHNIQUE OF MEASUREMENT

HAROLD M. MOONEY

ABSTRACT

Susceptibility determinations have been made on 200 outcrops of 11 rock types, using a three-coil induction instrument. Measurement is effective over a hemisphere of 50 cm radius. Data are given to show that the instrument is much less sensitive to rock surface irregularities than any previously described. Measuring circuits consist of 975 cycle oscillator, mutual inductance bridge, and two-stage amplifier. Investigation of errors shows that surface irregularities remain most important. Calibration by calculation is checked against ferric chloride standards through small samples taken at each outcrop. Data are given to show: 1) rock variability makes the check inconclusive, 2) variation of susceptibility within outcrops for gabbro and basalt is of the same order as variation between outcrops, 3) small-sample measurements show greater variation than large-sample measurements.

INTRODUCTION

This report and one to follow ("Part II: Field Results") are part of a susceptibility study intended to help interpret magnetic surveys in Minnesota. Many field surveys have been made in the state during the last sixty years; the need for susceptibility data has increased with the extensive use of the airborne magnetometer. The U. S. Geological Survey, in cooperation with the Minnesota Geological Survey, has flown 35,000 square miles since 1947 and plans to cover three-fifths of the state.

The present study provides susceptibility data on all important formations in the Minnesota pre-Cambrian except for the iron formations which are so highly variable as to present a separate problem. Three points of general interest beyond Minnesota will be emphasized here: 1) a new technique for measuring magnetic susceptibility on rocks in place, 2) the variability of susceptibility over short distances, and 3) the relation between susceptibility and petrography for individual rocks.

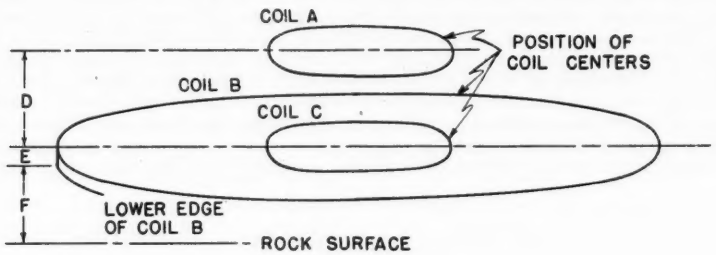
PREVIOUS WORK

Laboratory measurements of susceptibility on small samples of rock have been made by many workers during the last 60 years. Koenigsberger (1) gives an extensive bibliography through 1937; Nagata (2) and Haalck (3) list further references. As noted by Haalck, most such determinations have been made in fields of 50 oersteds and more. Werner (4) illustrates the uncertainty introduced by extrapolation to the earth's field of 0.5 oersted.

Measurements on rocks in place offer certain advantages, some of which are mentioned by Patterson (5): 1) the physical and chemical state of the rock is unaltered. The rock need not be broken, pulverized, or otherwise disturbed. In this way volume susceptibility is measured directly, without reference to den-

sity or to mass susceptibility. 2) Sampling errors should be minimized. The effective volume of rock under measurement is several thousand times greater than for small-sample determinations. 3) Direct correlation with geology can be carried through more easily and reliably.

Three methods have been described for measuring susceptibility in place although no field work has been reported. Paterson (5) measured the change in self-inductance produced in a coil when laid on a rock. Duffin (6) adjusted the height of an induction-type mine detector until the susceptibility of the rock



D = 9.3 CM. (VARIABLE TO ADJUST MUTUAL INDUCTANCE)
E = 1.6 CM.
F = 3.3 CM. WITH COILS ON ROCK
= 118.5 CM. WITH COILS ON TRIPOD

	COIL A	COIL B	COIL C	
RADIUS (CM.)	9.8	31.0	9.8	
NUMBER OF TURNS	227	200	200	# 29 FORMEX
RESISTANCE (OHMS)	39.1	109.0	34.5	
SELF INDUCTANCE (MH)	27.2	74.9	18.539*	*EFFECTIVE VALUE, DETERMINED INDIRECTLY
MUTUAL INDUCTANCE WITH COIL C (MH)	-2.334	+2.543		CALCULATED

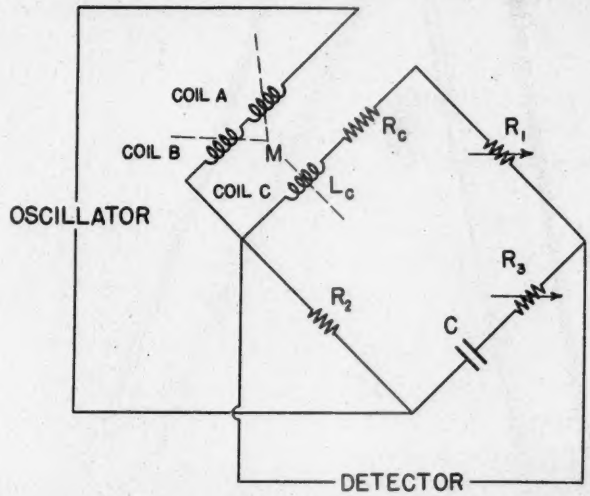
FIG. 1. Arrangement of coils and table of characteristics.

produced a standard signal. Kalashnikov (7) used a fluxmeter to determine the effect of the rock on two pairs of axially-offset coils. The present method uses the induction-balance principle common to the last two with a coil arrangement which greatly reduces errors due to rock surface irregularity.

DESCRIPTION OF APPARATUS

The three coils of the induction balance are arranged as shown in Figure 1. Mutual inductance is measured by means of the circuit of Figure 2. Wooden forms support the coils. A few brass parts were used in assembly, but no metal was used in any position which varied between readings. For example, base readings away from the rock are made on an all-wood tripod. Figure 3 shows a view of the apparatus.

The bridge circuit has been adapted from a standard mutual-inductance type. In this form the bridge has three desirable features: 1) Balance conditions are independent of frequency, so oscillator stability is not critical. 2) Both variable adjustments are resistive. Convenient and reliable variable resistors can be obtained commercially. The Helipot, for example, is a helically wound rheostat, linear within ± 0.5 percent and equipped with a 1,000 division dial. 3) Balance conditions are independent, which permits quick, accurate balancing.



BALANCE CONDITIONS

$$M = CR_2\left(R_C + R_1\right)$$

$$M = \frac{L_C}{1 + \frac{R_3}{R_2}}$$

CIRCUIT COMPONENTS

$C = 0.01$ MFD.
$R_1 = 0-1{,}000$ OHMS
$R_2 = 100$ OHMS
$R_3 = 0-15{,}500$ OHMS

FIG. 2. Diagram of bridge circuits.

Certain electrical characteristics of the circuit are given below. A complete circuit diagram is available on request.

Oscillator: Feedback type using duo-triode (1G6) with LC tuning in grid circuit. Frequency 975 cps. One stage voltage amplification (1G4) transformer coupled to push-pull power output (1G6). Two-plates-to-line output transformer, 15 volts output across bridge.

Bridge: Precision wire-wound fixed resistors, mica condenser, Helipot Type A variable resistors. Individual shorting switches across fixed resistors in R_1 and R_3 for coarse control, Helipots for fine control. Smoothing condensers across input to improve waveshape. 10 feet of 2 conductor shielded cable to coils, plug connection at each end.

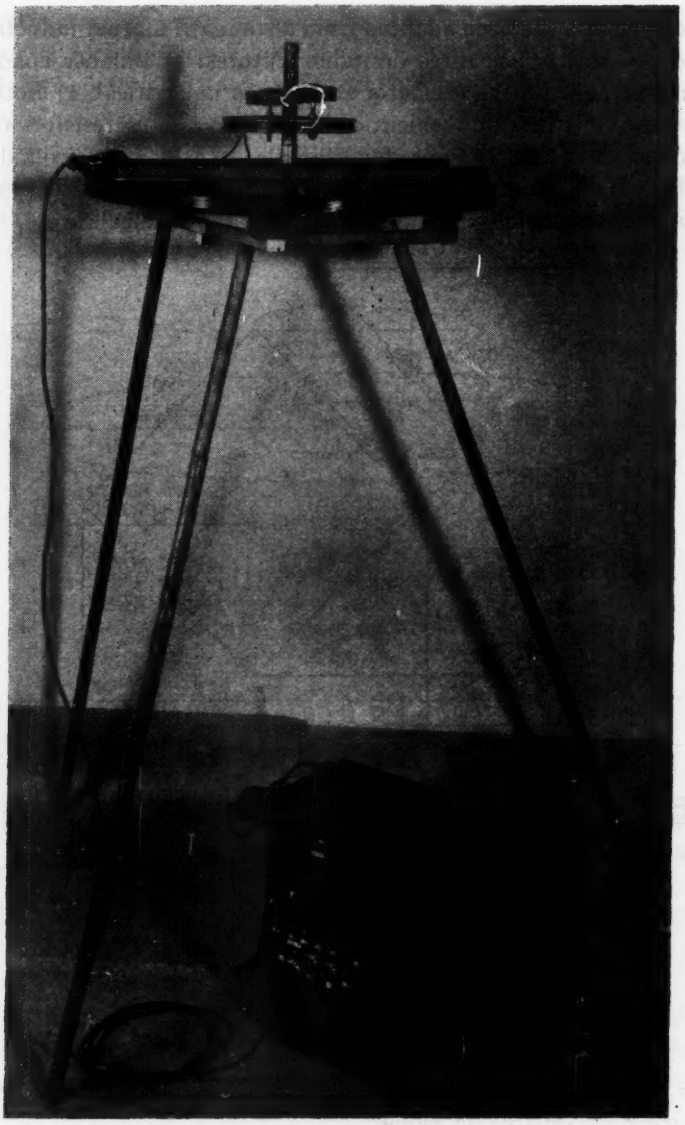


FIG. 3. Photograph of susceptibility apparatus.

Detector: RC-coupled, two stage amplifier (1U4's) with cathode follower output (1G4) to phones. Step-up transformer input to volume control preceding first stage. Tuned to 575 cps to reduce harmonics. Maximum voltage gain, input transformer to phones: 1325. Gain down $\frac{1}{2}$ db at $f=975$ cps, 4 db at $2f$, 25 db at $5f$.

Power Supply: 90 volts @ 35 ma, 1.5 volts @ 0.4 amps.

It is necessary to relate a change in coil characteristics to the resulting change in bridge balance conditions. Let it be assumed that the coil constants have become $M+\Delta M$, $L_c+\Delta L_c$, and $R_c+\Delta R_c$; the bridge is now found to balance at $R_1+\Delta R_1$, $R_3+\Delta R_3$. By substituting these new values into the balance conditions (Fig. 2) it may be shown that

$$\Delta R_3/R_3 = (M\Delta L_c - L_c\Delta M)/(L_c - M)(M + \Delta M) \qquad (1)$$

where the changes are not restricted to small values because products such as $\Delta R_3\Delta M$ have not been dropped.

THEORY

The principal theoretical problem is to calculate the change in self and mutual inductance produced in the coils by the magnetic susceptibility of the rock on which they are laid. The rock is assumed to have a flat surface and to extend to considerable depth. These assumptions will be examined later.

The mutual inductance between two coaxial circular coils can be expressed in several forms. One of the more convenient for calculation involves complete elliptic integrals of the first and second kind, $K(l)$ and $E(l)$:

$$M = 8\pi n_1 n_2 \sqrt{r_1 r_2}\,[(1 - l^2/2)K - E]10^{-8} \text{ microhenries}, \qquad (2)$$

where $l^2 = 4r_1r_2/[(r_1+r_2)^2+z^2]$, and n, r, and z represent respectively number of turns, radius in cm, and axial offset in cm. Smythe (8, p. 313) derives an equivalent equation. Tables of elliptic integrals may be found, for example, in Dwight (9, p. 199–205).

The change in self or mutual inductance due to the rock can be calculated in terms of the mutual inductance between a particular coil and the image of the same or another coil. The image, of strength $(\mu-1)/(\mu+1) = 2\pi k/(1+2\pi k)$, is located at the reflection position. (Here μ and k represent magnetic permeability and susceptibility of the rock.) To illustrate, the mutual inductance between two coplanar coils 5 cm above the level surface of a rock of susceptibility k would be determined from the above formula with $z=0$. The change in mutual inductance due to the rock would be calculated by the same formula with $z=10$ and M multiplied by $2\pi k/(1+2\pi k)$.

The given problem can be solved by these methods. The mutual inductance between coil C and coils A and B is the difference between the separate effects, since the currents in A and B flow in opposite directions. Similarly, the change due to the rock must be calculated as the mutual inductance between coil C and the images of coils A and B. The change in self-inductance of coil C is the mutual inductance between C and its image.

It is convenient to separate each of the results into a factor G dependent upon the geometry of the system and a factor $k/(1+2\pi k)$ involving only rock susceptibility. The calculated values may then be written in the form $\Delta M = G_1 k/(1+2\pi k)$

and $\Delta L_c = G_2 k/(1+2\pi k)$, where each G is the sum of one or more terms of the form:

$$16\pi^2 n_1 n_2 \sqrt{r_1 r_2}\,[(1 - l^2/2)K - E]10^{-3} \text{ microhenries.}$$

Typical values for G_1 and G_2 are 9,608 and 10,220 microhenries, calculated for the particular dimensions shown in Figure 1.

These expressions for ΔM and ΔL_c may be substituted into equation (1) to yield a relationship between rock susceptibility and the change in bridge balance conditions produced by it. Approximating $(L_c - M)$ by L_c, the result is

$$\Delta R_3 = \frac{k}{1 + 2\pi k} \frac{(R_2 R_3/R_2 + R_3)G_2 - R_3 G_1}{M + G_1(k/1 + 2\pi k)}. \tag{3}$$

This equation provides the theoretical basis for the present work. G_1 and G_2 are

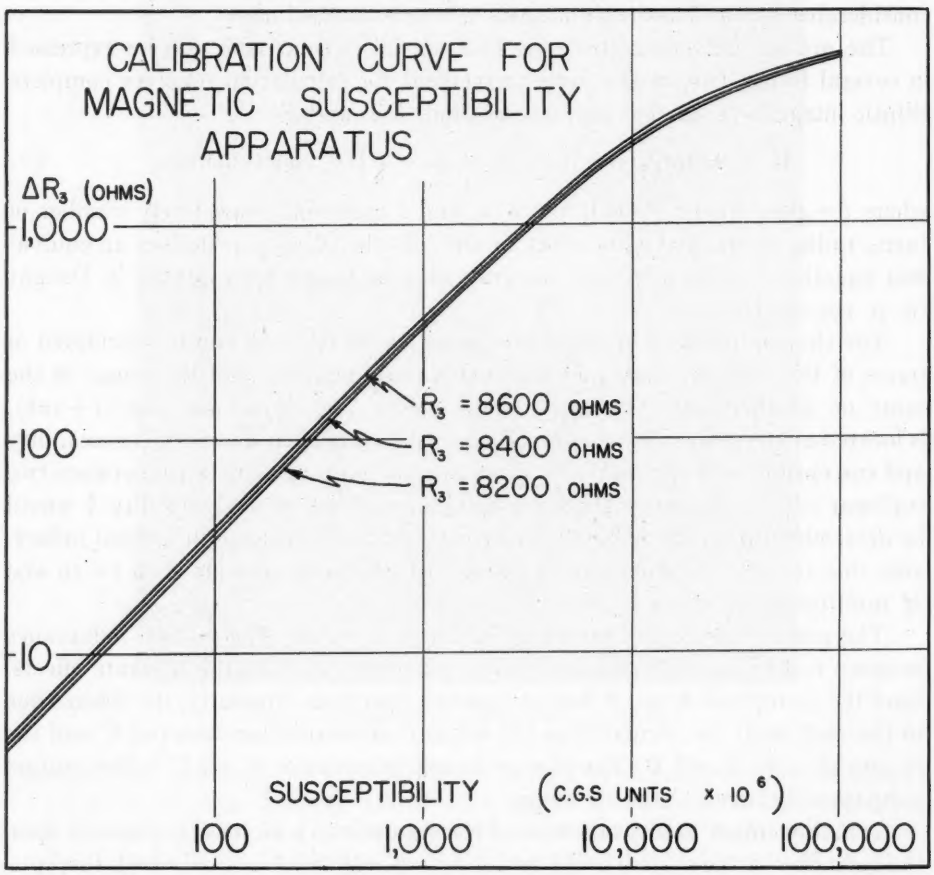


FIG. 4. Calibration curves. ΔR_3 is the change in R_3, for bridge balance, produced by setting the coils on the rock.

calculated from coil geometry, while the bridge readings give R_3 and (from the balance conditions) M. In principle M should be constant for a given coil arrangement, but temperature change and mechanical shock produce small changes which cannot be neglected. For this reason each susceptibility determination is preceded by a base reading of R_3, on a tripod well away from the rock. A small correction for the effect of the rock must be applied to the tripod reading. Figure 4 shows the final calibration curve, ΔR_3 against k with R_3 as parameter.

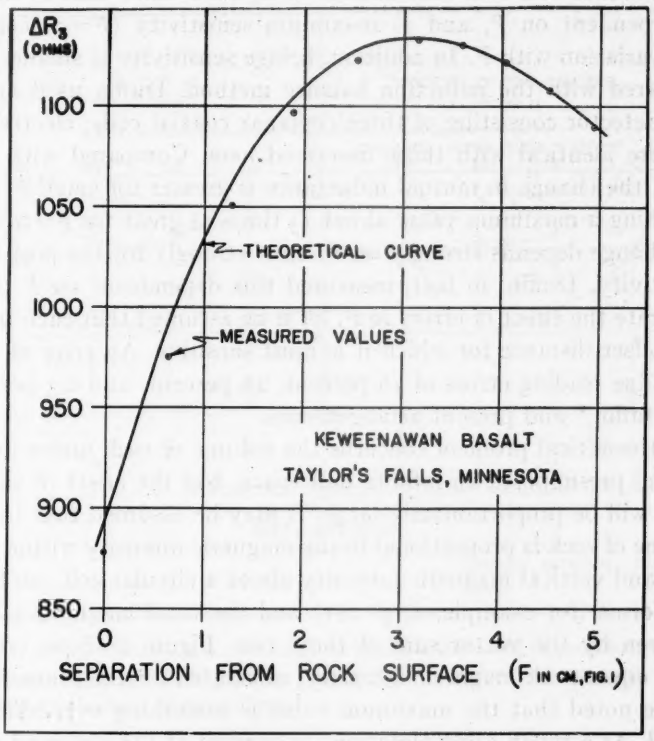


FIG. 5. Theoretical and experimental variation of bridge reading with separation of coils from rock surface.

Equation (3) may be used to show the existence of an optimum coil offset from the rock (dimension F in Figure 1). This optimum offset is characterized, for a given susceptibility, by maximum ΔR_3 and relative insensitivity to variations in F. The resulting values for G_1 and G_2 show a smooth variation with F; G_1 passes through a maximum at about 3 cm while G_2 drops off sharply from $F=0$. Typical values for $F=0$, 3, 5 cm are $G_1=7{,}345$, 9,635, 9,190 uh; $G_2=32{,}720$, 11,820, 6,810 uh. Since G_1 is relatively more important than G_2 in equation (3), ΔR_3 passes through a maximum, at $F=3.3$ cm. It will be noted that the last term in the denominator of equation (2) is unimportant except for large k, which means

that the optimum value of F is approximately independent of k. Figure 5 shows the calculated variation of ΔR_3 with F, together with experimental data taken on a Keweenawan basalt.

It is of interest to consider the effect of errors in offset distance F on the instruments proposed by Paterson (5) and Duffin (6). Such errors cannot be avoided; they arise, for example, if the rock surface is irregular or if one edge of the coil rests on a pebble. Paterson measured the change produced by a rock in the self-inductance of a coil. Calculations of G_2 vs. F show that 1) this change is strongly dependent on F, and 2) maximum sensitivity ($F=0$) coincides with maximum variation with F. In addition, bridge sensitivity is smaller by a factor of 4, compared with the induction balance method. Duffin used an induction-type mine detector consisting of three coplanar coaxial coils; electrical coil connections were identical with those described here. Compared with the present instrument, the change in mutual inductance is greater for small F (F less than 5 cm), reaching a maximum value about 13 times as great for $F=0$. Again, however, this change depends strongly on F, most strongly for the position of maximum sensitivity. Duffin, in fact, measured this dependence on F to determine k. To illustrate the effect of errors in F, let it be assumed that each instrument is set at the offset distance for which it is most sensitive. An error of $\frac{1}{2}$ cm would produce bridge reading errors of 16 percent, 16 percent, and 0.3 percent for the Paterson, Duffin,* and present arrangements.

A final theoretical problem concerns the volume of rock under investigation. Equation (1) presupposes an infinite half space, but the effect of the rock close to the coils will be proportionately large. It may be assumed that the effect of a given volume of rock is proportional to the magnetic intensity within the volume. The radial and vertical magnetic intensity about a circular coil can be expressed in several forms (for example, 8, p. 271) and the total magnetic intensity at a point is given by the vector sum of these two. Figure 6 shows cross-sectional contours of equal peak magnetic intensity, calculated for the geometry of Figure 1. It will be noted that the maximum value is something over half the earth's normal field. As a rough approximation, 90 percent of the observed effect is due to the rock within a hemisphere of radius 50 cm. The contours of maximum intensity will be changed by the magnetic properties of the rock; this effect is about 2 percent for susceptibility 0.002 cgs, but does not in any case affect the susceptibility determinations for a homogeneous rock.

SOURCES OF ERROR

Temperature change and *mechanical shock* affect the dimensions, hence mutual inductance, of the coils. Bridge balance is subject to irregular *instrumental drift*. Errors due to these effects can be easily detected and kept insignificant by alternate readings on rock and tripod.

* Dr. Duffin points out that he reduces this source of error by measuring differences only for two offsets of the order of a foot. The instrument thus operates at low sensitivity.

Distributed capacitance and inductance produce variations from the ideal bridge circuit and balance conditions of Figure 2. Electrical components were arranged to minimize coupling. In addition, a least squares solution was made for the apparent value of bridge components, using standard inductances in place of the coils. As may be seen in Figure 4, however, measured susceptibility depends primarily on the change in R_3 and only secondarily on R_3 itself. This secondary dependence applies also to the other bridge components. For this rea-

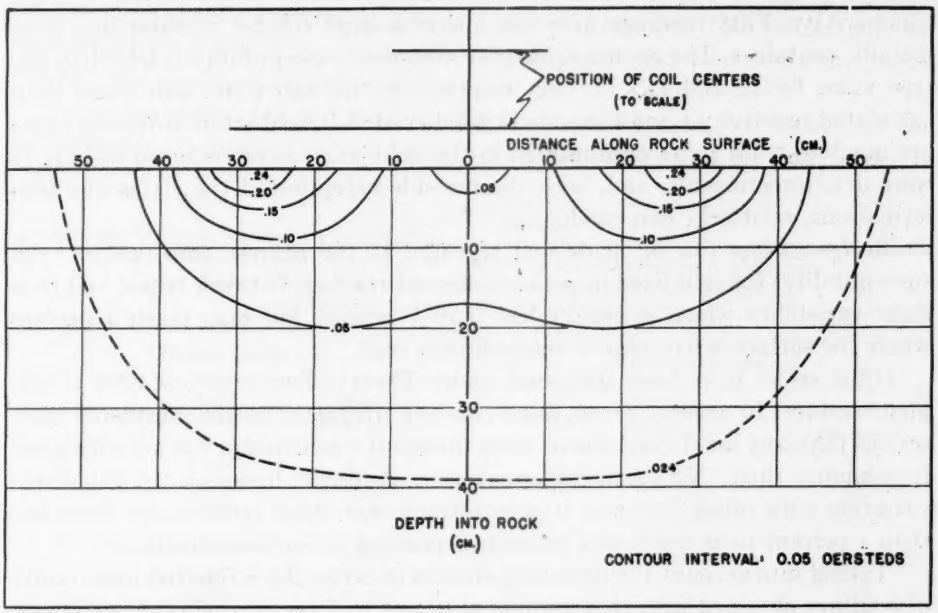


FIG. 6. Cross section through rock, showing calculated distribution of peak magnetic intensity Dotted line includes all magnetic intensities greater than 10 percent of maximum, and may be interpreted as effective volume of measurement.

son, the distributed effects determined by experiment were lumped into an apparent value for L_c, given in Figure 1.

The calibration data of Figure 4 include a correction for *tripod error*, the rock effect when the coils are on the tripod.

Remanent magnetization of the rock produces no effect on susceptibility determinations by alternating current. A study of remanent magnetization is beyond the scope of this report.

Demagnetization depends on sample shape, grain size, and susceptibility. Several theoretical studies (for example, Puzicha, 10) show that, for magnetite disseminated in nonmagnetic material, the apparent susceptibility differs from the true value by roughly 2 percent for $k=0.01$ and 30 percent for $k=0.1$ cgs. This correction has been applied to readings on rocks with apparent susceptibility

greater than 0.01, but two facts should be noted: 1) few rocks other than iron formation require the correction, and 2) apparent susceptibility *before* correction is the quantity of interest for magnetic interpretation. *In situ* measurements yield this quantity, but small-sample measurements do not.

In principle, *rock conductivity* should affect the first but not the second bridge balance condition (Fig. 2); calibration is in terms of the latter. Distributed capacitance (including coil-to-rock) and inductance, however, will produce some cross-feed, and experiments were run to measure dependence of the results on rock conductivity. Fifty readings were taken over a large volume of water in a non-metallic container. The results show that measured susceptibility is less than the true value by 11 and 14×10^{-6} cgs respectively, for tap water and water with calculated resistivity 1,300 ohm-cm. It is believed that field errors from this cause are much less, for rocks encountered in the field work to be reported in part II were dry, impermeable, and, with the possible exception of the slates and iron formations, relatively non-conducting.

Bridge settings can be made and repeated to the nearest ohm (3×10^{-6} cgs susceptibility) for coils fixed in position. Repeat readings between tripod and rock show variability which is usually less than 1 percent but may reach 4 percent where the surface is irregular or susceptibility high.

Offset errors have been discussed under Theory. Few outcrops offer a true plane surface. In general, errors due to surface irregularities are considered more serious than any mentioned above, even though the instrument has been designed to minimize them. No precise information is available; based on the calculated variation with offset distance, it is estimated that these errors range from less than 1 percent to as much as 5 percent, depending on surface smoothness.

Taking into account the preceding sources of error, the estimated uncertainty of readings obtained with this equipment is 20×10^{-6} cgs or 3 percent, whichever is larger.

CALIBRATION

Calibration by calculation has been described, but experimental checks are desirable. The best check would use measurements over different materials of known susceptibility. No such materials are available in sufficient volume.

Field readings can be checked indirectly against determinations on small rock samples taken at the outcrops. A small-sample apparatus can be calibrated against standards such as ferric chloride. The small sample, however, may not be representative of the rock or of the large sample; this uncertainty made measurements in place seem preferable, and data given below confirm the difficulty.

A small-sample apparatus of the type described by Duffin (6) was constructed. Three coaxial coils of 200 turns, spaced about 5 cm apart, were wound on a hollow wooden form of 2 cm radius. A 50 cc sample of rock chips inserted part way into the form changes the mutual inductance relationships just as for the large-sample coils. Electrical characteristics were chosen to permit use of the same measuring circuit.

The maximum volume susceptibility of ferric chloride solution is about 70×10^{-6} cgs. Since calibration to 0.1 cgs was desired, the calibration curve was compounded from a single point based on several ferric chloride samples and a slope based on various mixtures of sand and taconite. Taconite susceptibility was not known, but the volume susceptibility of such a mixture is proportional (neglecting demagnetization effects) to the weight percent of taconite.

Small-sample data were taken on rock samples from each of the 200 large-sample field locations. The precision of these measurements roughly equals that for the large-sample apparatus, 20×10^{-6} cgs or 3 percent. The instrument can be reset within 8×10^{-6} cgs or 1 percent; repacking of the same rock chips in the sample tube produces variations of the same order.

As a first check, the 200 large-sample readings (L) were plotted against the small-sample readings (S) (on a logarithmic scale, because of the large range of

TABLE I

SUSCEPTIBILITY DATA, SHOWING VARIATION WITHIN OUTCROPS, BETWEEN OUTCROPS, AND BETWEEN INSTRUMENTS. THREE VERTICAL READINGS ON EACH OUTCROP ARE SPACED 5–10′ APART; HORIZONTAL PAIRS ARE TAKEN AT THE SAME POSITION, AS CLOSELY AS POSSIBLE. UNITS: cgs$\times10^{+6}$

Duluth Gabbro			Keweenawan Basalt		
Outcrop	Large Instrument	Small Instrument	Outcrop	Large Instrument	Small Instrument
A	1,900	6,320	E	1,300	1,550
	1,920	1,930		1,920	880
	1,900	1,700		1,350	600
B	980	1,230	F	4,800	5,160
	1,550	2,510		120	100
	2,050	2,700		1,600	2,850
C	880	140	G	3,700	940
	830	260		1,610	620
	870	1,210		2,900	1,740
D	1,140	1,310	H	1,850	480
	1,410	1,560		1,480	1,660
	1,280	1,480		1,810	960

susceptibilities). Perfect agreement would produce a straight line: $\log L=\log S$. A least squares fit gives the line: $\log L=0.382+0.871\log S$ with a high correlation coefficient 0.95, but the points scatter widely about the line. The least squares line deviates from the expected line by less than the precision of measurement. This suggests that the calculated calibration is satisfactory, but does not account for the scatter.

To find the source of the scatter, four outcrops each of gabbro and basalt were studied in detail. The rock types, with roughly equal susceptibility, cover extremes in grain size. Compared with other rock types studied, susceptibility variability is about average. Three large-sample readings were taken on each

outcrop at 5–10 foot intervals; a small sample was taken as close as possible to each location. Table I lists the results, from which several conclusions can be drawn:

1) The results represent real variations within and between rocks, for the variation exceeds by many times the precision of measurement.

2) Differences between instruments for the same outcrop are very much smaller than differences between and within outcrops. An analysis of variance (variance = standard deviation squared) applied to Table I shows that variance within outcrops roughly equals variance between outcrops, while variance between instruments is smaller than these by a factor of 80. Clearly the method can provide only a rough check on accuracy of calibration.

3) The large-sample method shows less scatter than the small-sample method. The sum of variances about outcrop means is more than twice as great (2.07) for the latter. This is on the borderline of statistical significance by the F test (5 percent level, 16 and 16 degrees of freedom, criterion F greater than 2.33).

As a general conclusion, susceptibility data to be used for magnetic interpretation should be based on several readings. Large-sample and small-sample data to be given in Part II are for the most part averaged from two or more readings.

SUMMARY OF CONCLUSIONS

1) Compared with previous methods of measuring susceptibility on rock outcrops, this method reduces the error due to irregularity of the rock surface by a factor of 10 or more.

2) Effective rock volume under measurement is roughly a hemisphere of radius 50 cm.

3) Estimated precision of measurements is 20×10^{-6} cgs or 3 percent of reading, whichever is greater. The most important uncertainty remains rock surface irregularity.

4) Calculated calibration is not inconsistent with an indirect check against a ferric chloride standard, but large variations in rock properties make the method inconclusive.

5) Magnetic susceptibility data have little more than order-of-magnitude significance for magnetic interpretation unless based on several samples. This applies to both small and large sample methods but more strongly to the former.

ACKNOWLEDGMENTS

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NOTE ON THE RADIO-TRANSMISSION DEMONSTRATION AT GRAND SALINE, TEXAS*

WM. M. BARRET†

ABSTRACT

Some three years ago a group of scientists witnessed a demonstration involving the propagation of strong radio signals from a surface transmitter to a receiver located 700 feet below the surface in a salt mine at Grand Saline, Texas.

Since that time two misconceptions have arisen concerning the demonstration, namely: (1) that the signals were not transmitted through the earth, but instead, reached the receiver by travelling through the mine shaft, and (2) that considerable power was required at the transmitter, which implied high earth attenuation of the signals.

This paper presents evidence that denies these beliefs.

INTRODUCTION

On December 11, 1948, William M. Barret, Inc. demonstrated (1) to members of various technical societies, and to representatives of the U. S. Navy and Air Force, that radio waves could be transmitted from a portable transmitter at the earth's surface to a receiver located at a depth of 700 feet in abandoned workings of the Kleer Salt Mine at Grand Saline, Texas.

Before making the demonstration, elaborate precautions were taken at the top and bottom of the mine shaft to insure that no radio signals could reach the receiver through air or metal at the shaft. Moreover, after taking these precautions, rigorous tests were made which proved conclusively that the radio signals actually travelled through the earth from the transmitter to the receiver, rather than through the vertical shaft to the 700-foot level and thence through air and/or salt to the receiver.

In recent months it has been learned that a number of geophysicists, including some of those attending the demonstration, are of the firm opinion that the strong radio signals received in the demonstration did in fact enter the mine through the shaft, and then followed the path of least attenuation through tunnels and salt to the receiver. Furthermore, another belief has developed that much power was required at the transmitter, and accordingly the earth attenuation of the signals must have been large.

Because of the divergence of opinion on these questions, and in view of the current interest in the earth attenuation of radio waves, it is thought desirable to describe briefly one of the tests that was made to prove that the signals did not enter the mine through the shaft, but instead traversed an earth path from the transmitter to the receiver; and also, to outline another test that provided

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results which deny the concept that much power was needed at the transmitter to overcome high earth attenuation.

EXPERIMENTAL CONTRADICTION OF TRANSMISSION THROUGH SHAFT

Figure 1(A) shows a plan view of the 700-foot level of the Kleer Mine and five positions occupied by the transmitting antenna on the earth's surface. Throughout the tests under consideration, and during the demonstration, the receiving antenna was located at the 700-foot level, vertically below the most northern position indicated for the transmitting antenna, and its axis was oriented into the same vertical plane that contained the five positions of the transmitting antenna, which are identified by the letters C to G, inclusive.

The transmitting antenna was a tuned doublet made up of two collinear 120-foot insulated cables stretched along the ground and fed in the center by a tuning and coupling device which was energized through a coaxial cable by a nearby portable transmitter that generated continuous unmodulated waves having a frequency of 1,602 kilocycles per second. The receiving antenna was an untuned 240-foot insulated doublet placed flat on the mine floor and center connected to a battery-driven Hammarlund SP-400-X receiver provided with a rectifier-type output meter which derived its input from an attenuator that was tied in immediately ahead of the final push-pull audio stage.

For the test under discussion, the transmitting antenna successively occupied the five positions shown in Figure 1(A), and for each position the power input to the transmitter's final stage was maintained within 10 percent of a constant value. Meanwhile, the receiver was operated at constant gain and its output was measured quantitatively. Figure 2 illustrates graphically the relation between the receiver output (for transmitting Positions C to G) and the horizontal distance, or spread, between the transmitter and receiver. In this figure the receiver readings were adjusted for the slight differences in transmitter power.

It is to be noted in Figure 2 that when the transmitter was at Position C, which was vertically above the receiver, the reading of the receiver was but 10 microamperes, which represented the noise level of the receiver; that the maximum signal was observed at a spread of about 700 feet, and that with increasing spread the received signal continually declined.

In order properly to evaluate the curve of Figure 2, one must consider the wave paths involved in the transmission. It has already been shown (2) that the transmitting antenna used in the demonstration propagates a strong surface wave along the earth's surface in the direction of the receiver, and that as this wave moves along the ground it is progressively refracted into the earth along substantially parallel ray paths. The angle at which the rays are refracted downward into the earth is determined by the refractive index of the surface and near-surface media, and in turn the refractive index is governed by the electrical conductivity, dielectric constant, and magnetic permeability of the media, as well as the frequency of the surface wave.

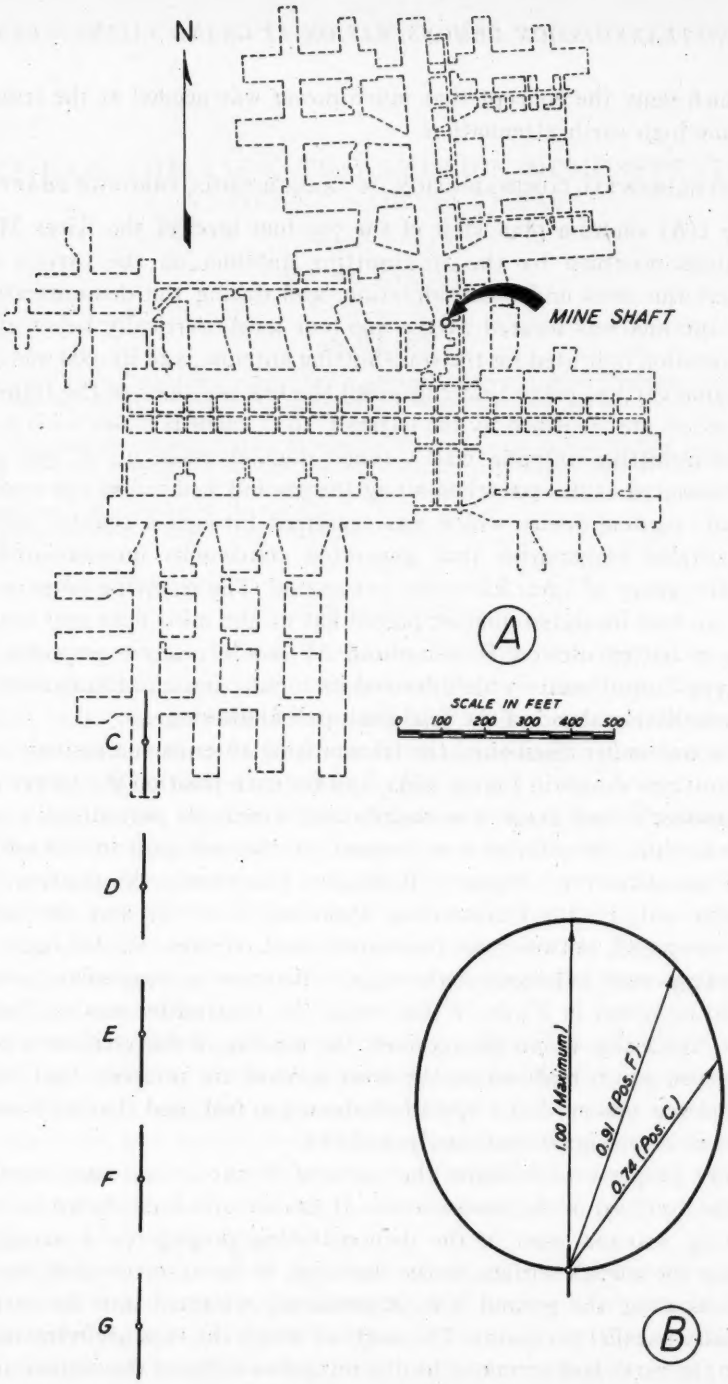

FIG. 1. (A) Plan view of 700-foot level at Kleer Salt Mine, and five positions occupied by transmitting antenna on earth's surface. Receiving antenna was located under, and in same vertical plane with, transmitting antenna at Position C. During demonstration, transmitting antenna occupied Position F. (B) Forward horizontal field pattern of transmitting antenna, with vectors indicating direction and relative magnitude of radiation from Positions C and F to mine shaft.

Under the conditions existing in the Grand Saline demonstration and tests, the average slope of the refracted ray paths was approximately 45 degrees, and for spreads equal to or greater than the depth of the receiver, it is believed that the major portion of the received energy travelled along these parallel refraction paths. Such was the condition for the demonstration, when the spread was 1,000 feet. It was also the case for the test data of Figure 2 when the spread reached and exceeded 700 feet. But for spreads substantially less than the depth of the receiver, the radio energy is believed to have travelled directly through the earth

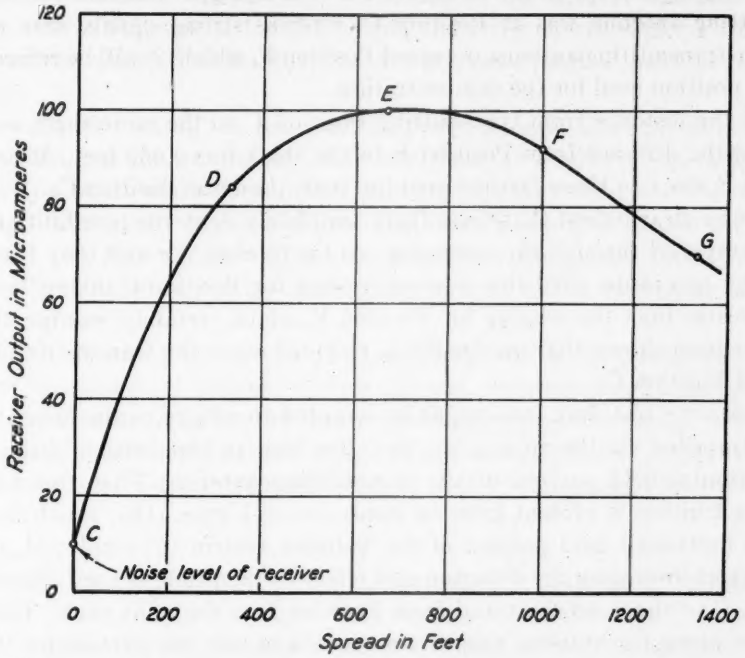

FIG. 2. Relation between receiver output and spread when successively transmitting from Positions C to G. Note that no signal was received when transmitter was at Position C, which was nearest position to mine shaft.

from the transmitting antenna to the receiving antenna, and both the transmission and reception of this energy was influenced by the like vertical field patterns of the antennas.

Inasmuch as there was no radiation at right angles to the axis of the transmitting antenna (3, 4, 5), and accordingly no reception at right angles to the axis of the receiving antenna, it is easy to understand why Figure 2 indicates that no signal was received when the transmitting antenna was at Position C, which was vertically above the receiving antenna. As the spread between the antennas increased from zero to about 700 feet, the configuration of the vertical field patterns of the antennas was such as to cause more and more energy to travel directly

through the earth from the transmitter to the receiver. When the spread approximated the 700-foot depth of the receiver, and the dominant transmission was via the surface wave and parallel refraction paths, the highest receiver reading was observed. Successive increases in spread to Positions F and G resulted in a progressive decline in the receiver output, due to similar decreases in the amplitude of the surface wave before being refracted into the earth, and thence to the receiver.

Aside from providing evidence in support of the suggested transmission paths, the most significant disclosure of Figure 2 is that no signal was received when the transmitting antenna was at Position C, whereas strong signals were received when the transmitting antenna occupied Position F, which, it will be remembered, was the position used for the demonstration.

Now the distance from transmitting Position C to the mine shaft was 1,175 feet, and the distance from Position F to the shaft was 2,060 feet. Accordingly, Position F was 1.75 times farther from the shaft than was Position C.

It seems clear indeed that these facts completely deny the possibility that the signals travelled through the mine shaft to the receiver, for had they been propagated by this route, then the receiver reading for Position C should have been much greater than the reading for Position F, which certainly was not the case, for it has been shown that no signal was received when the transmitting antenna occupied Position C.

Despite the test data, one might be tempted to adhere to the belief that the signals travelled via the mine shaft, and then seek an explanation of the data in the horizontal field pattern of the transmitting antenna. That this argument would be fruitless is evident from an inspection of Figure 1(B), which shows the forward horizontal field pattern of the antenna system (6) employed, together with vectors indicating the direction and relative magnitude of the radiation from Position C to the mine shaft and from Position F to the mine shaft. Taking the radiation along the antenna axis as 1.00, it is seen that the vectors for Positions C and F were respectively 0.74 and 0.91, which means that the radiation in the direction of the shaft for Position C was but 19 percent less than that for Position F, and obviously this difference may be ignored as an explanation of the observed data.

On the basis of the test outlined here, and because of other confirming evidence, it therefore seems certain that the signals observed in the Grand Saline radio demonstration did not reach the receiver through the mine shaft but did in fact travel an earth path from the transmitter to the receiver.

TRANSMITTER-POWER CONSIDERATIONS

As already pointed out, the other question raised in connection with the demonstration concerns the belief by some that a comparatively large amount of power was required at the transmitter to propagate signals to a depth of but 700 feet, and therefore the earth attenuation of the signals must have been high.

In answering this question it should first be stated that a quantitative deter-

mination of the attenuation was not attempted, for this would have required a knowledge of the reflection coefficient of each lithologic boundary traversed by the radio energy, and these coefficients could neither be measured nor estimated within reasonable limits.

However, it can be stated with certainty that a comparatively large amount of power at the transmitter was not required to propagate signals to the receiver. This very question was investigated by gradually reducing the transmitter power to find the lowest level at which good loud-speaker volume could be maintained at the receiver. During this test, and at all times, the receiver was operated at less than half its full sensitivity. As before, the receiver was under Position C; the transmitter was at Position F, which was the same position used for the demonstration.

The engineers making the test were surprised to learn that the power input to the final stage of the transmitter could be reduced to the lowest operable value, which was 3.0 watts, and still maintain good loud-speaker volume at the receiver. Assuming a combined antenna and final-amplifier efficiency of 50 percent, which is probably too high for the apparatus employed, the power radiated would amount to but 1.5 watts, which is a little less than the power used by an ordinary 3-cell flashlight.

The fact that strong signals could be heard from such a low-power transmitter after travelling along the ground for some 300 feet, thence through approximately 470 feet of sediments including freshwater sands, about 25 feet of cap rock carrying 5 to 9 feet of salt brine, some 400 feet of salt and 100 feet of air, provides irrefutable evidence that the transmission was both effective and efficient.

CONCLUSION

In view of the results of the two tests described, it may safely be concluded that:

1. The signals did not travel via the mine shaft in the Grand Saline radio demonstration.

2. Considerable power was not required at the transmitter to propagate signals to the receiver.

3. The reception of strong signals with but 1.5 watts of radiated power does not set quantitative bounds for the earth attenuation, but it does provide indisputable evidence that the attenuation must have been very low.

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STUDIES OF A SURFACE SEISMIC DISTURBANCE*

JOSEPH D. EISLER†

ABSTRACT

Seismic studies in a caliche covered area revealed existence of a prominent surface wave group. The dispersive characteristics of this wave group and the existence of retrograde elliptical particle motion place it in a class of Rayleigh waves. Examples of vertical as well as two-component motion are presented.

In the course of seismic investigations in a caliche covered area of southeastern New Mexico, the existence of a prominent surface wave group was established. This paper deals with some of the more outstanding seismological characteristics of this wave group which were recorded and analyzed.

The most notable feature of the area in which these experiments were carried out is the presence of the near-surface caliche. This sedimentary rock permeates the near-surface stratigraphy and appears to vary lithologically both in vertical and lateral dirctions. The near-surface stratigraphy, as determined from drill cuttings, is shown in Figure 1. The section consists of:

0–2′	soil cover
2–70	sandy caliche
70–110	sand to calichey sand
110–130	sandy caliche
130–150	gravel
150–170	yellow clay
170–190	crystalline limestone
190–210	yellow and red clay
210–230	sand and gravel

The velocity function obtained from uphole data is also shown in Figure 1. These data suggest two major compressional velocity layerings as follows:

0–30 feet	surface zone—low velocity (3,000′/sec).
30–230 feet	subsurface zone—high velocity (7,800′/sec).

In order to make a study of the characteristics of this prominent wave group, two types of studies were performed: recordings were obtained for a succession of short spreads between two shot point locations using six vertical component geophones, and three-component geophone studies were performed at a number of points along the line of shot points. The layout of shot holes and geophone spreads is shown in Figure 2. Continuous linear coverage for vertical geophones was used with geophone interval of 50 feet and separation of spreads of 25 feet. Two three-

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component stations were located along the first half of the line of spreads at 275-foot interval with station separation of 25 feet. For each setup of geophones, shots were fired from each end of the test location.

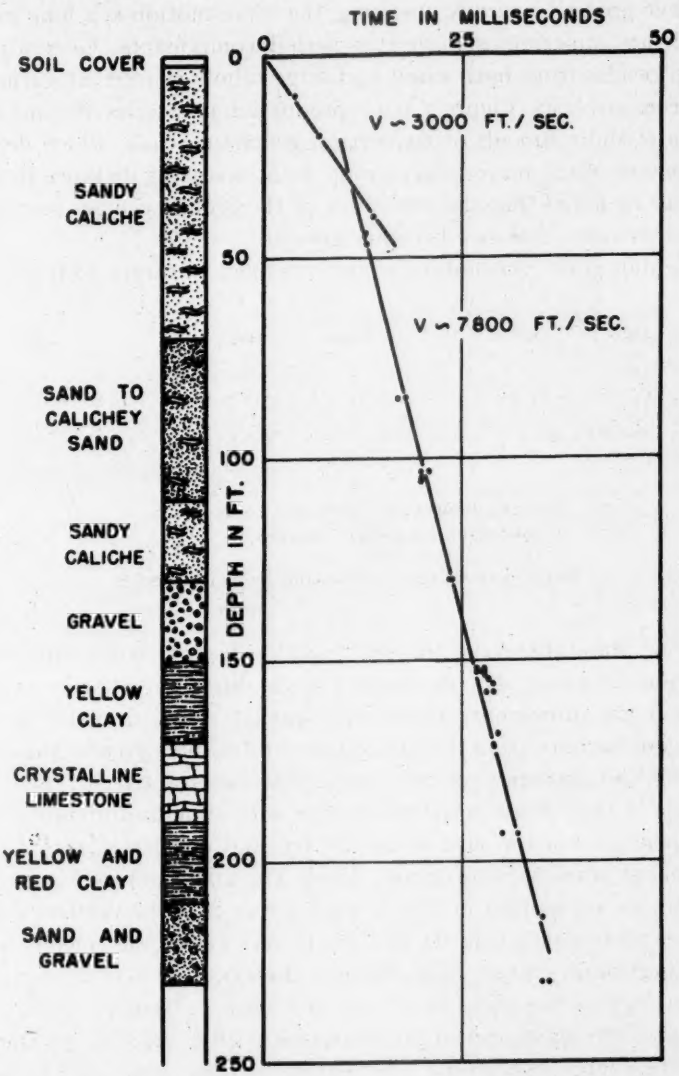

FIG. 1. The near-surface stratigraphy and velocity function at the test site.

Equipment used in these experiments was substantially flat in response from approximately 7 cps to 300 cps. The geophones, having a natural frequency of 4.5 cps, were fed through an expander type flat amplifier to high frequency galvanometers. Three-component geophones used during one phase of this investiga-

tion had a natural frequency of 4.5 cps and each component was arranged to be separately planted.

The ground motion appears on the vertical component geophone spreads as a complex wave group. Generally speaking, the wave motion is a long-period wave upon which are superimposed shorter period components. Generation of this wave group results from both small and large inhole charges at variable depths as well as from airblasts. Figure 3 is a reproduction of a series of shots taken with a succession of short spreads of six vertical geophones each, which demonstrates the development of the major wave group with increasing distance from the shot point. It may be noted that the amplitude of the group becomes more prominent as the geophone shot distance becomes greater.

Near the shot point, the motion is poorly defined and trace-to-trace correlation

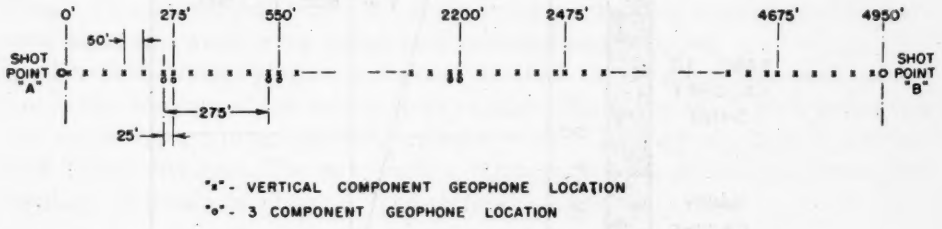

FIG. 2. Layout of shot holes and geophone spreads.

is difficult. At these distances the only notable feature is low amplitude long-period motion ($T=0.10$ sec) of about $\frac{1}{2}$-cycle duration. Shorter period waves ($T=0.03$ sec) are prominent. These short-period waves decrease in amplitude with increasing distance from the shot point. At distances greater than 1,000 feet, the nature of the predominant wave group becomes apparent. The significant characteristic is that phase relations change with time and distance, indicating marked dispersion. For the sake of clarity, tracings of selected recordings of vertical component stations were made. These are presented in Figure 4. In this figure, the traces are shifted in time in such a way that the vertical line connecting the traces represents a velocity of 1,800 ft/sec. This is the velocity with which the energy maximum travels. The effect of dispersion is best exemplified in the group of tracings on the right-hand side of Figure 4. Here the individual peaks and troughs of the wave appear to propagate with a velocity greater than the velocity of the energy as a group. The velocity of these peaks and troughs ranges from 1,900 to 2,700 ft./sec. This velocity represents approximately the phase velocity of a particular frequency over a moderate distance. This relative shift of the various components of motion causes an apparent reappearance of a group pattern at certain intervals of travel distance. These intervals are of the order of 1,000–1,200 feet. Thus at intervals of 500 to 600 feet, the character of motion can be approximately correlated by inverting one of the traces with respect to

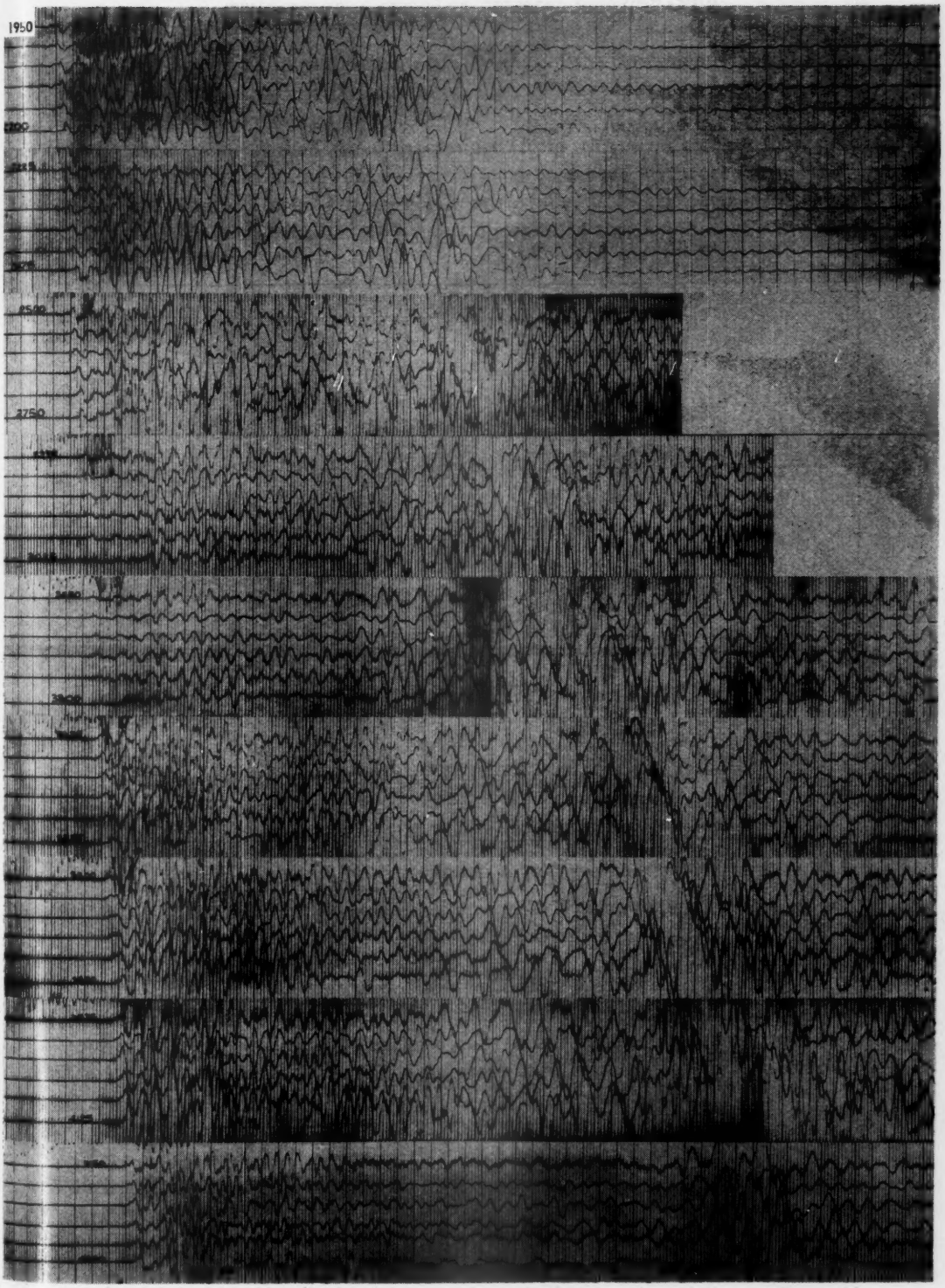

FIG. 3. A series of records showing shots for a succession of short spreads using vertical component geophones. This series demonstrates the development of the major wave group with increasing distance from the shot point.

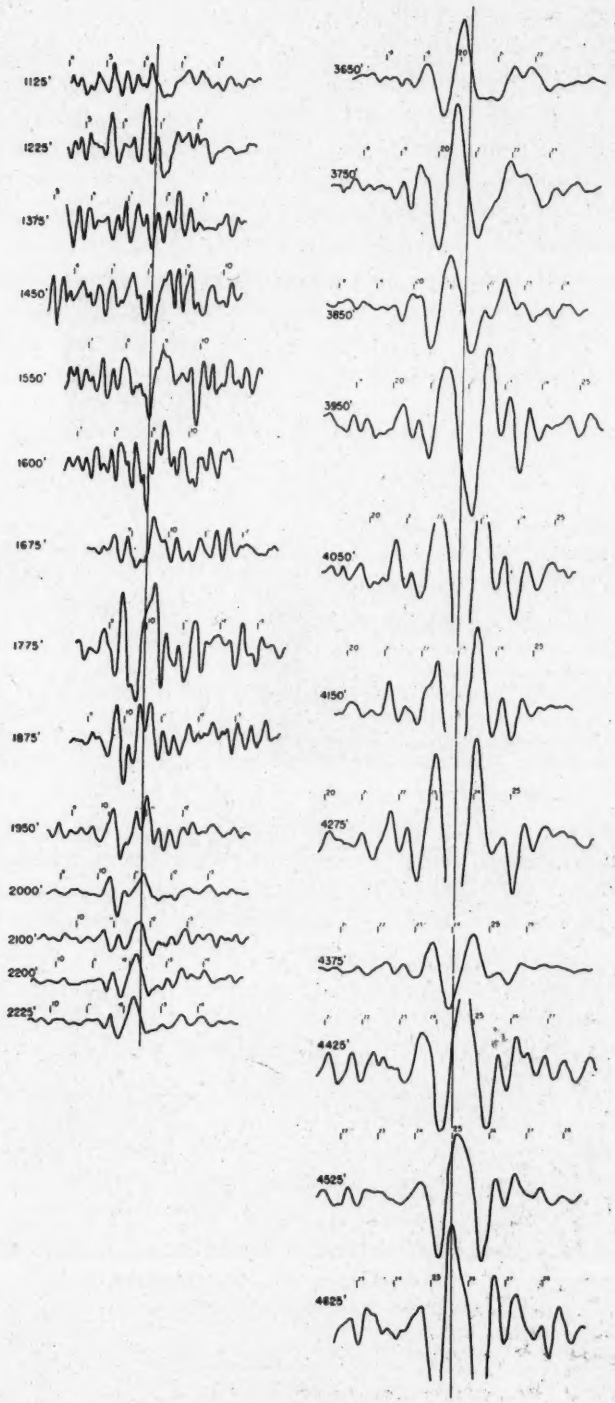

FIG. 4. Tracing of selected vertical geophone outputs showing the dispersive nature of the wave.

the other. Figure 5 shows the time-distance plot of the prominent wave group using time limits bracketing the maximum energy. This plot represents the value of minimum group velocity.

Particle velocity has been determined from three-component recordings. These indicate that motion in a vertical plane is orbital in nature and describes ellipses of modified form. The motion is retrograde, i.e., when particles are above their position of equilibrium they move opposite to the direction of wave prop-

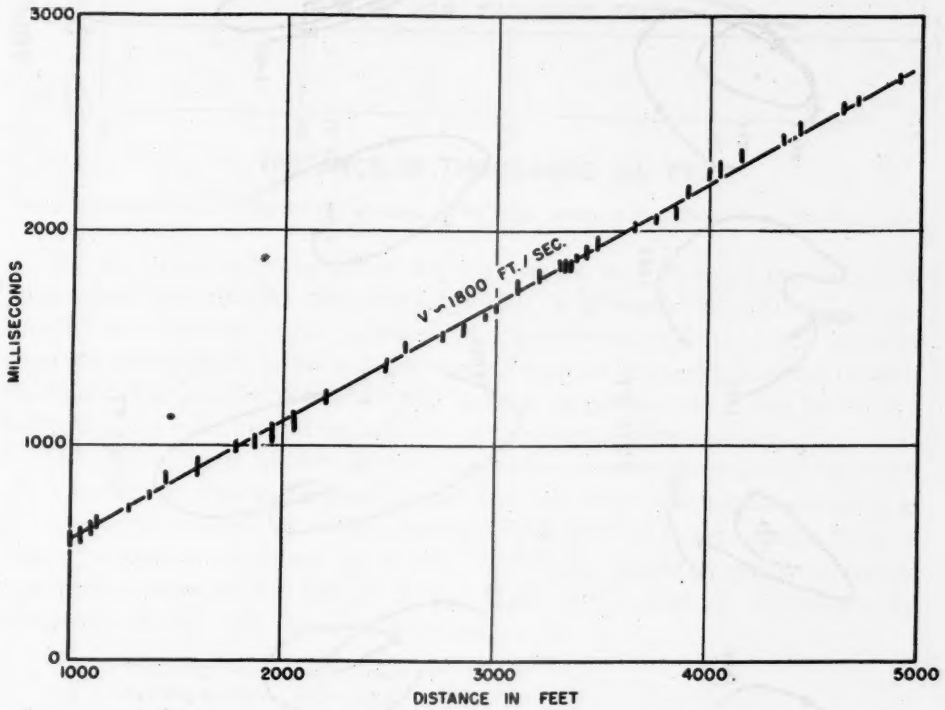

FIG. 5. Time distance plot of the prominent wave group in which the time limits bracketing the maximum energy are indicated.

agation and when they are below their position of equilibrium, they move in the direction of wave propagation. This corresponds to the familiar Rayleigh wave motion. Particle trajectory diagrams constructed from Z and X component of velocity are shown in Figure 6. The plots represent the loci of the resultant XZ vectors of velocity.

An outstanding feature of the particle trajectory is the major orbit of 1 to 1½-cycle duration. The period of this orbit appears to increase with increasing distance. On the major orbit are superimposed smaller retrograde orbits of shorter period. Terminal motion is more irregular, but elliptical, which grades into either shear or dilatational motion.

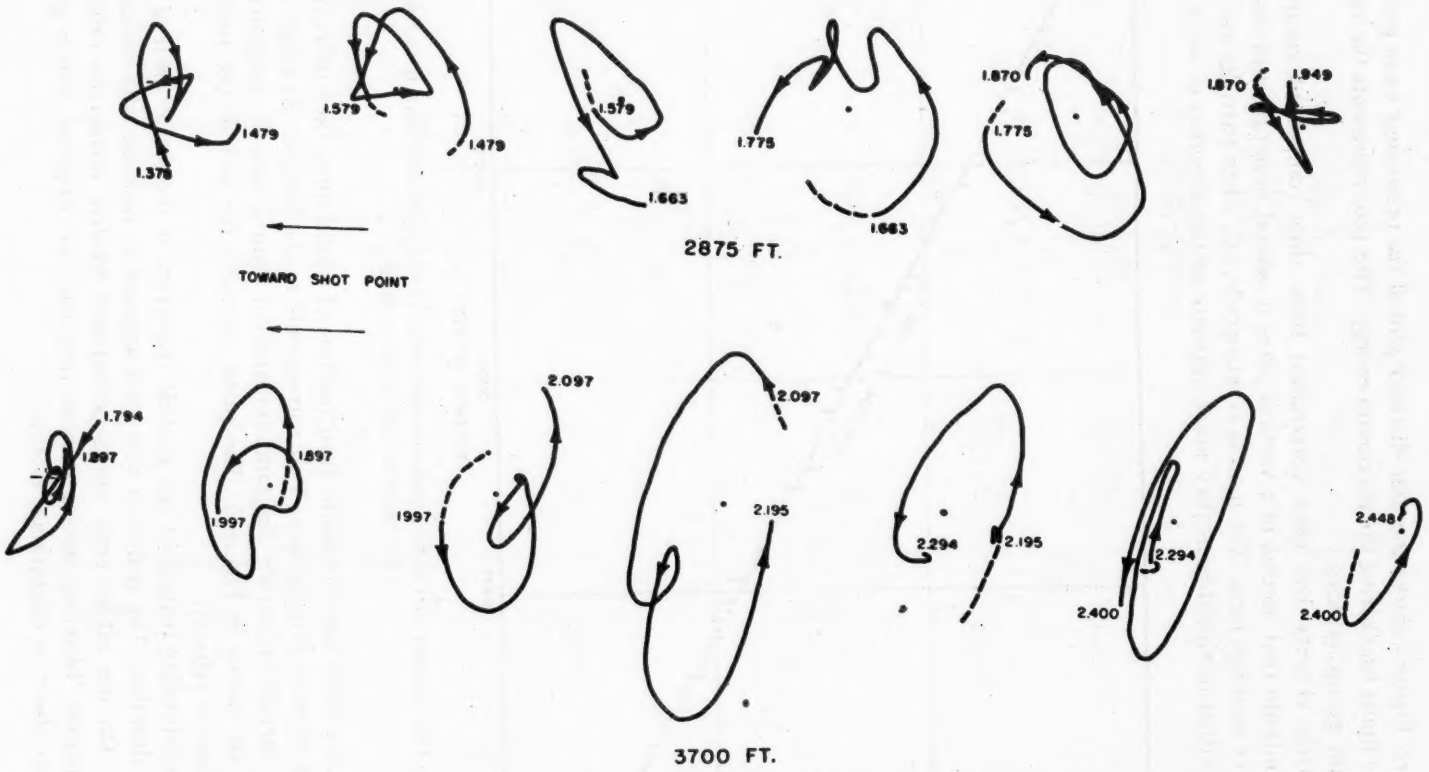

FIG. 6. Particle trajectory diagram constructed from the vertical and in-line horizontal component geophone outputs.

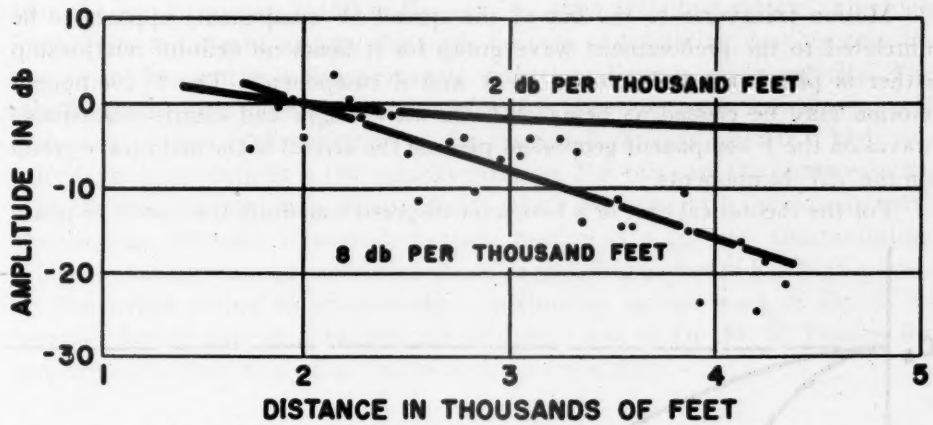

FIG. 7. Theoretical and observed attenuation of Rayleigh waves with distance from the shot point.

The theoretical attenuation of Rayleigh waves with distance from the shot point obeys the relation that the amplitude is inversely proportional to the square root of distance, which amounts to approximately 2 db per 1,000 feet. The observed attenuation shown in Figure 7 was found to be greater than the theoretical value. The possible reason for this increase in attenuation is loss by friction and scattering which is not included in the theoretical consideration.

The plot in Figure 8 illustrates the observed increase in the period of the maximum amplitude with increasing distance from the shot. The period increases at a rate of approximately 20 ms per 1,000 feet. This increase in period with distance cannot be entirely explained by classical theory for dispersive media. A partial explanation proposed by Jeffries is that higher frequencies are attenuated by scattering, leaving only lower frequencies.

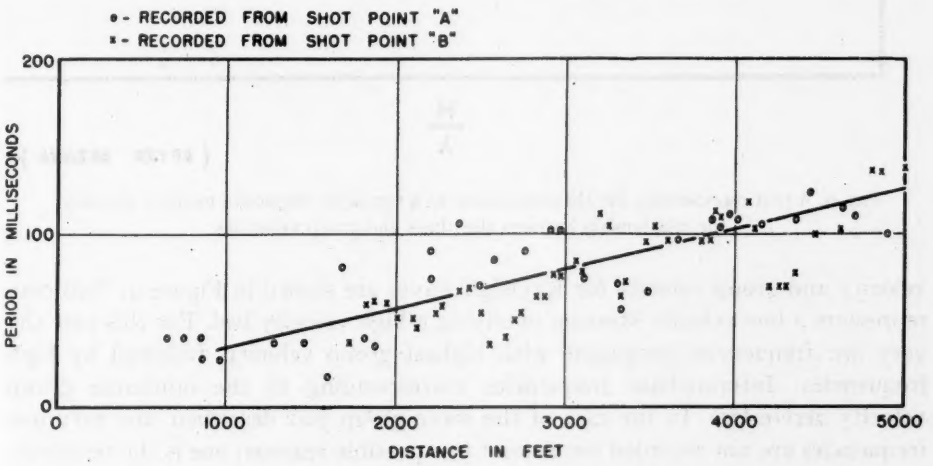

FIG. 8. Observed increase in the period of the maximum amplitude of the major wave group with increasing distance from the shot point.

Motion transverse to the line of the spread (Y component) appears to be unrelated to the predominant wave group for it bears no definite relationship either in phase or amplitude to the X and Z components. The Y component motion may be classed as being of Love wave origin and clearly identifiable waves on the Y component geophones precede the arrival of the main wave group on the ZX components.

For the theoretical case of a two-layer dispersive medium the curves of phase

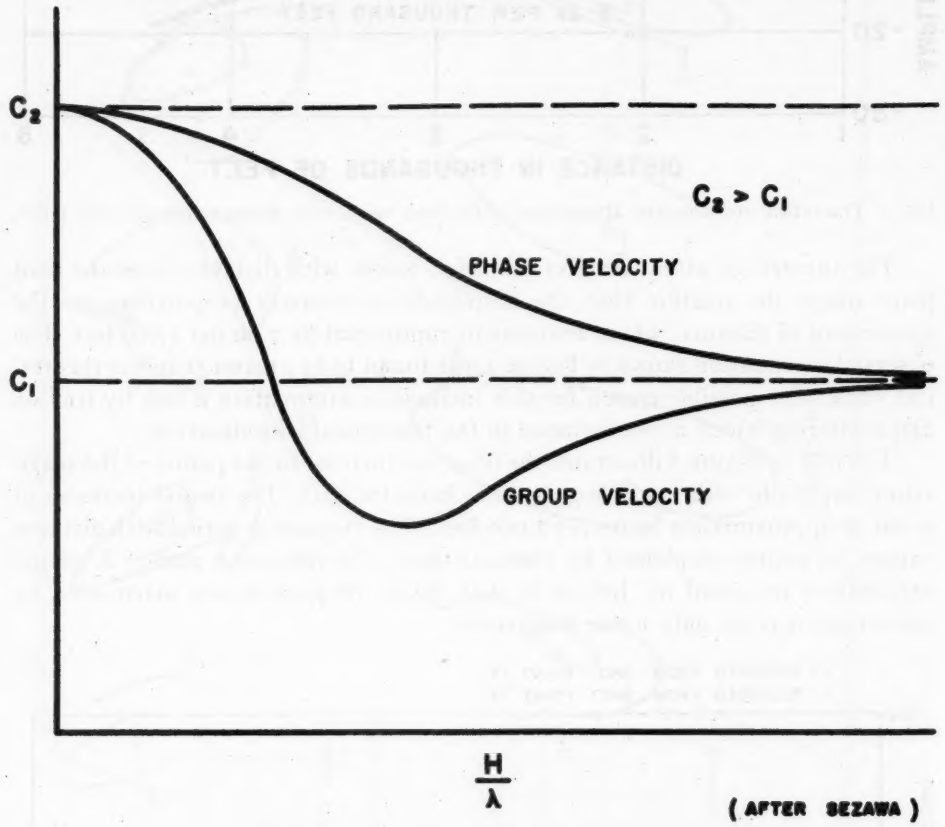

FIG. 9. A plot representing the theoretical case of a two-layer dispersive medium showing the relationship between the phase and group velocities.

velocity and group velocity for Rayleigh waves are shown in Figure 9. This case represents a low velocity stratum overlying a high velocity bed. For this case the very low frequencies propagate with highest group velocity, followed by high frequencies. Intermediate frequencies corresponding to the minimum group velocity arrive last. In the case of the wave group just described, the very low frequencies are not recorded for at least two possible reasons; one is the relatively small degree of excitation of low frequencies by an explosive point charge; and

two, the low frequency cutoff of the velocity type recording system. The high frequencies are absent at long distances because of scattering, leaving only intermediate frequencies which propagate with the minimum group velocity. The relative progression of peaks and troughs within the wave group indicates normal dispersive pattern of Rayleigh waves for the two-layer case wherein a high velocity layer is overlain by a low velocity stratum. For this case the phase velocity is higher than the minimum group velocity which conforms with the experimental observations. Definite retrograde particle motion is a further substantiating evidence that the wave group observed can be placed in a class of Rayleigh waves.

The writer wishes to acknowledge contribution to this work of Dr. S. T. Martner for his part in obtaining the field data and of Dr. M. E. Denson for carrying out certain analytical phases of this investigation.

THE DEVELOPMENT OF A NEW METHOD OF SEISMIC VELOCITY DETERMINATION*

F. P. KOKESH†

ABSTRACT

The conventional method of making velocity surveys in bore holes is inherently expensive, time consuming, and inconvenient, and has a tendency towards non-uniformity of results.

With increasing recognition of the importance of seismic velocity information in the evaluation of seismograph data, the attention of geophysicists is turning towards means of overcoming the obstacles standing in the way of obtaining velocity information in greater volume.

Considerable interest has recently been aroused in a new method of measuring seismic velocities wherein the explosive charge is placed in the hole and the seismic energy is picked up with multiple detector groups placed on the surface. Experimentation carried on during the past year indicates that the new method is quite workable.

Casing perforator guns of the conventional bullet type have given results to depths exceeding 8,000 ft. with complete safety. Some experimentation with primacord as the explosive has given encouragement as a means of increasing the depth at which the method may be used. Substantial improvements have been made in the manner of obtaining the time break.

This paper attempts to outline the basic problems of velocities and their measurement and describes the preliminary development that has been done thus far on the new method of velocity measurement.

The seismograph method depends primarily on the simple relation of time and velocity, from which distances may be computed. For the arrangement shown in Figure 1, the equation is:

$$2Z = VT$$

where:

Z is the depth of reflecting bed
V is the average velocity
T is the two-way travel time

The application of the seismograph is relatively straightforward as long as the velocity V is constant, and the distance, or the depth, then becomes simply a function of time. Of necessity, in the absence of adequate velocity information, the velocity in a given area must be assumed to be constant.

It is, however, definitely established that velocities do vary from one area to another, so that velocity and time become equal partners in determining Z.

These lateral variations of velocities may account for certain anomalies which appear in a given seismic picture. Such anomalies are construed as being highs and lows, or thickenings and thinnings, whereas they are actually nothing more than velocity anomalies.

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This approach is not new. Velocity variation laterally is recognized in West Texas[1] and California, among other places,[2] and strong efforts are being made to cope with it. The requirement is a comparatively heavy concentration of velocity information in the area of interest so that a velocity distribution map can be plotted. In the application of these data, it has been found convenient by some to plot seismic data in terms of time rather than in terms of distance or depth, and then to interpret and re-interpret the time map for depth in terms of the velocity information as it becomes available.

VELOCITY MEASUREMENT

Seismic velocity may be determined by at least three methods, namely:

1) by refraction shooting;
2) by reflection shooting;
3) by direct measurement over a vertical interval in a bore hole.

Only the third method gives the full accuracy required for detailed reflection work.

Velocity determinations in a well are sometimes referred to as "well shooting." This term, however, is not sufficiently definitive. The expression "velocity survey" as applied to a particular well will be used in this paper.

In spite of the recognized need for extensive and accurate velocity information, these data are sparse in many areas, even where a large number of wildcats and field wells have been drilled. This is, to a considerable extent, because of the fact that the presently accepted method of making velocity surveys is generally very expensive, inconvenient, and time-consuming.

Velocity surveys in bore holes until recently have been made almost entirely by exploding dynamite in shallow shot holes near the surface location of the well and picking up the resultant seismic energy from successive shots at various depths in the well by means of a suitable seismometer lowered into the well on a cable provided by a well logging company. At the surface, the cable is connected to the input of a conventional seismograph instrument truck. The travel time to various depths is thus measured and plotted, along with curves of the derived average velocity and interval velocity.

Ordinarily, this involves shutting down a seismic party in the field and bringing it with its equipment to the well. Inasmuch as shot holes must be drilled and other preparations made prior to the survey, the crew must be brought in somewhat earlier than the moment the well is actually available. Since wells are seldom ready at the moment predicted, and since a number of services are usually run in the well ahead of the velocity survey, it is not uncommon for the seismic crew to be tied up for a considerable time before it starts its work. At roughly $1,000 per crew day, this becomes rather expensive, aside from the attendant disruption of the crew's field program.

Another important point must be remembered. Absolute velocity measurements are difficult to achieve; and under the present method, velocity surveys

are made by a variety of crews, using an equal variety of field techniques, including size of charge, type of detecting, amplifying and recording equipment, and interpretation of the records. The result is that one velocity survey may not be entirely comparable directly with another in a quantitative manner, and each user may have to reinterpret the data according to his own method before he can apply it.

The first requirement then is more velocity surveys, which can be practically met only by introducing a method which will surmount the above-mentioned obstacles of expense, inconvenience, and nonuniformity of results. The new method described hereafter has already proved to be valuable in this respect.

NEW METHOD OF VELOCITY MEASUREMENT

The idea of reversing the present practice of making velocity surveys—namely, to put the explosive into the drill hole, and pick up the seismic energy with seismometers at the surface—has occurred to many people. Mention is made of it in a small way in standard geophysical texts.[3] In fact, velocity surveys have been conveniently made in this way in shallow holes using dynamite caps or small dynamite charges as the explosive.

Several factors make this reverse method attractive, both technically and economically:

1) It is not necessary to bring a complete seismograph party to the well since shot holes are not required. All that is needed is a number of surface seismometers, simple amplifying equipment, and a recorder. The explosive can be provided by the company furnishing the well logging truck. This obviously makes a direct cut in cost.

2) It is not necessary to obtain permits to drill shot holes and shoot dynamite in the vicinity of the well.

3) When the explosive is placed in the hole, the explosive charge may not need to be so large as that used in shot holes. Conditions for efficient propagation of seismic energy in a bore hole at depth may be much better than those in shallow shot holes in unconsolidated material. At the same time, much greater sensitivity can be provided in surface seismometers than is practicable in well seismometers.

4) A large number of seismometer positions at the surface is possible when the explosive is in the hole, all positions recording simultaneously from a single shot. With the explosive at the surface, it is rather hazardous to put more than one seismometer group in the hole at one time.

5) At shallow depths of 3,000 or 4,000 ft, shots can be made in quick succession. Standard casing perforator guns can provide as many as 40 shots per trip in the hole, and the principal time involved is in moving the gun from one level to another. Tremendous detail can thus be obtained in a very short time. The present equipment allows at least five shots per trip for depths greater than 4000, ft which still is comparatively fast, since round trips can be made to 10,000 ft in an hour or less.

6) Good uniformity of results is possible, particularly if the seismic equipment is standardized.

There are some possible disadvantages. In areas of thick weathering, difficulty may be encountered in getting enough energy through the weathering to the surface seismometers. This can be overcome by increasing the size of the charge, but here there may be some limitations on the amount of explosive which can be detonated in a deep bore hole.

On this latter point, we do have some assurance, however, in the fact that

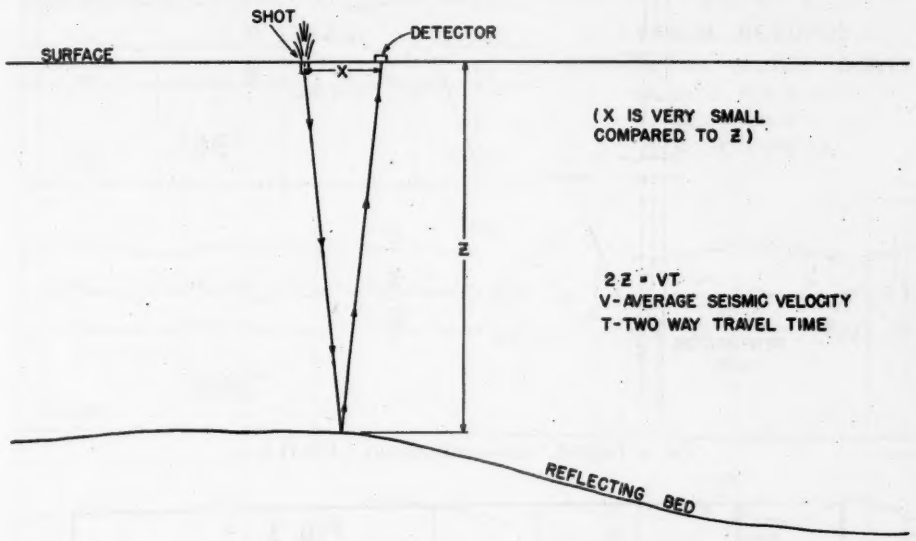

FIG. 1. The seismograph method of subsurface exploration.

perforator guns, both of the bullet and the shaped charge types, have been exploded a large number of times in open holes, and no sticking of the gun has ever been noticed. Other evidence is also accumulating to indicate that the danger of detonating explosives in open hole has been considerably exaggerated.

DEVELOPMENT OF NEW METHOD

The first substantial experimental test of the new method using standard well servicing guns was made in the California Company's No. 1 U.S.D.A. 2, Bude Field, Franklin County, Mississippi, in March, 1950. The encouraging results of this experiment were subsequently reported in detail in a paper written by A. Claudet and Neal Smith,[4] published by the Oil and Gas Journal. Considerable interest was aroused in the method as a result of this paper.

A schematic layout of the equipment used in this experiment is shown in Figure 2. Guns were lowered to various depths by means of a Schlumberger truck and cable. The gun firing circuit provided a time break which was fed into the seismic equipment provided by the American Exploration Company. No

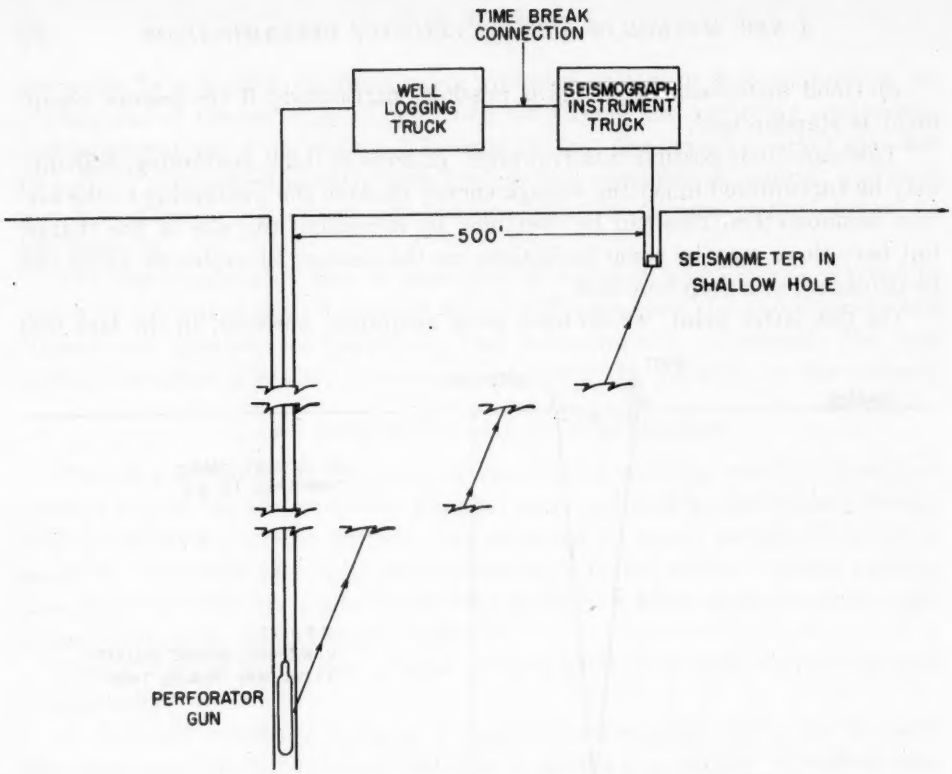

FIG. 2. Layout, California Company 1 U.S.D.A. 2.

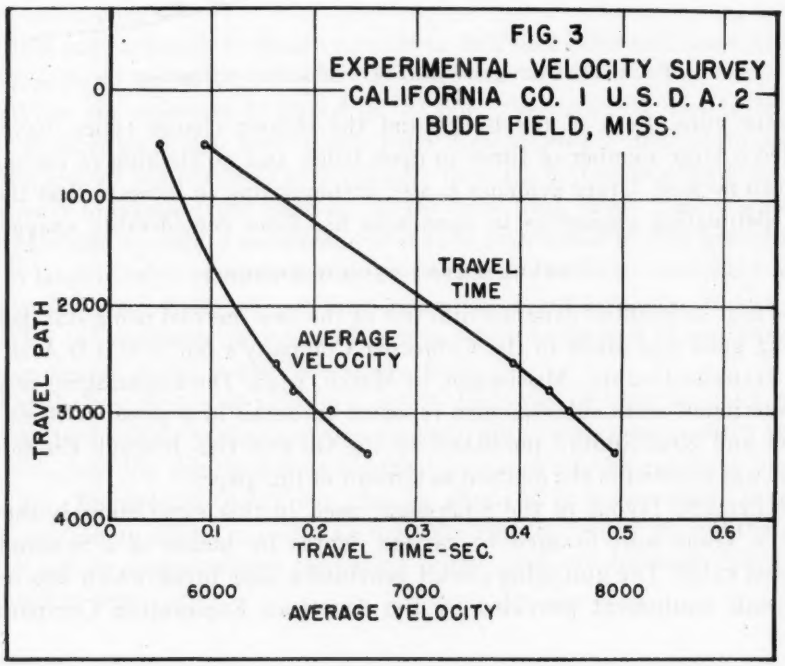

FIG. 3. Curves, California Company 1 U.S.D.A. 2.

difficulty was encountered in synchronizing the starting of the seismic recorder and the shooting of the gun.

It was hoped that velocity measurements could be made at the same time samples were being taken at depth, using the energy released by the sidewall gun. The energy of the sidewall gun was too small even at comparatively shallow depths. On the other hand, with a standard bullet perforator gun using a standard

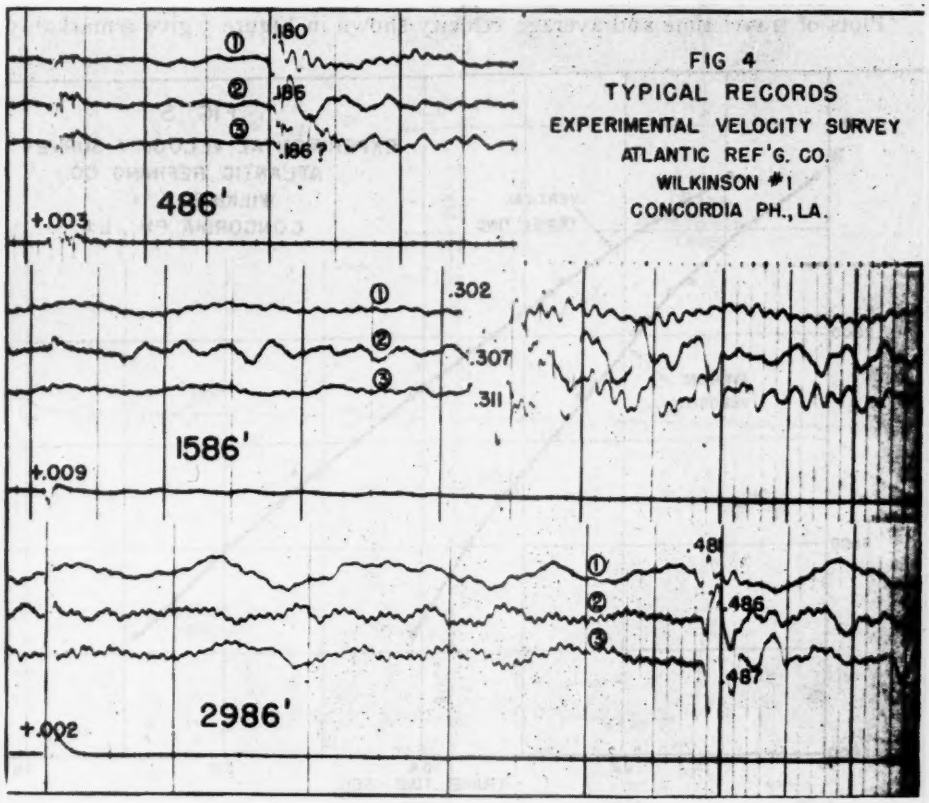

FIG. 4. Typical records, Atlantic No. 1 Wilkinson.

load of 24 grams of powder, results were obtained to a maximum depth of 3,400 ft. By using dummy bakelite bullets, it was possible to shoot the gun in casing.

The results of the few shots made yielded a very reasonable set of curves. Figure 3 shows plots of the travel time and the average velocity derived from the above-mentioned experiment.

The basic practicability of the method having been established, another substantially more elaborate experiment was made in February, 1951, in Atlantic Refining Company's No. 1 Wilkinson, Fairview Field, Concordia Parish, Louisiana. The general layout of equipment was the same as that shown in Figure 2.

Portable seismic amplifying and recording equipment provided by the General Geophysical Company was mounted in the recorder cab of the Schlumberger truck. Three groups of surface seismometers were located 800 ft from the well. Typical records are shown in Figure 4. Trace No. 3, connected to a group of 10 ordinary surface seismometers, gave substantially better results than traces No. 1 and No. 2 which were connected to a well seismometer and to a swamp type seismometer respectvely.

Plots of travel time and average velocity shown in Figure 5 give remarkably

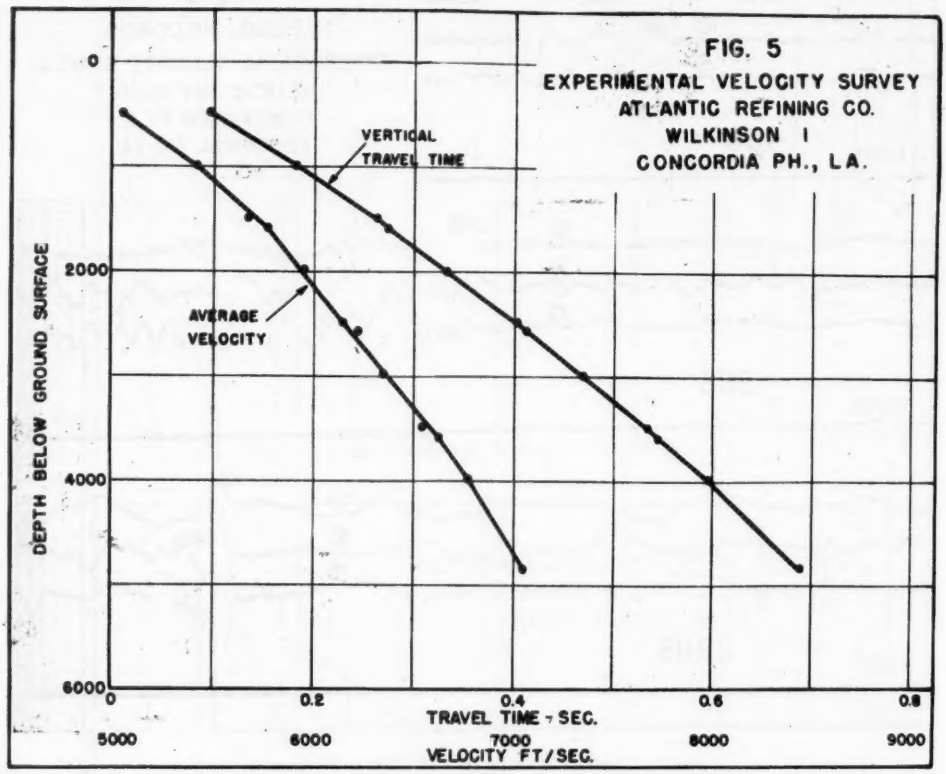

FIG. 5. Curves, Atlantic No. 1 Wilkinson.

smooth curves. Fairly reliable results were obtained to a depth of nearly 5,000 ft. The standard perforator gun gave results to about 4,000 ft. The additional depth was obtained by exploding simultaneously 24 shaped charges of the type used for casing perforations. Twenty-four shaped charges, while more powerful than a single standard perforator shot, would be quite uneconomical considering that an additional depth of only about 1,000 ft was obtained. Evidently, the shaped charge is not so efficient in imparting seismic energy to the ground as is the standard bullet gun.

INCREASED DEPTH PENETRATION

Greater depth penetration was the object of the next experiment made in April, 1951, in the Gulf Refining Company's No. 1 Doyle Lyons, wildcat, Jones County, Mississippi. Portable seismic equipment manufactured by Technical Instrument Company and provided by The Gulf Research Corporation was

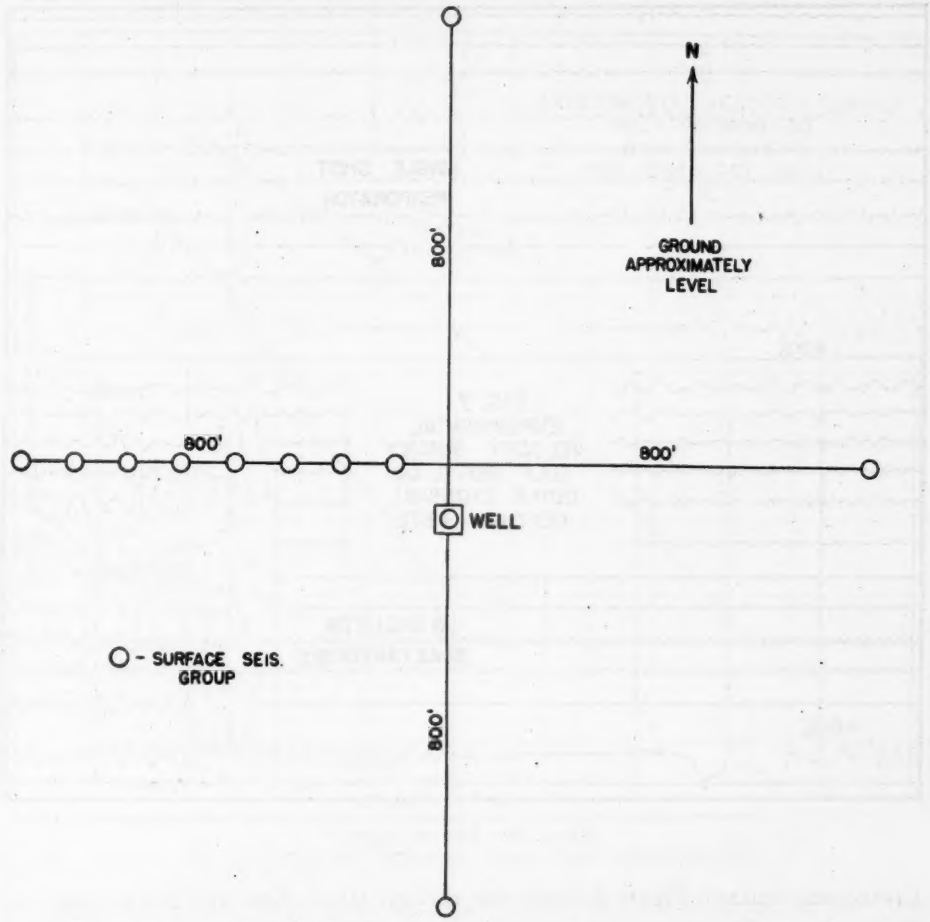

FIG. 6. Layout, Gulf Refining Company Doyle-Lyons, No. 1.

mounted in the Schlumberger truck cab. A rather elaborate arrangment of seismometers was used as shown in Figure 6. Each seismometer group consisted of 6 to 8 surface seismometers of the very small type.

In order to increase the energy, and thereby obtain greater depth, several standard perforator guns were modified slightly to permit shooting eight shots at a time. With a 40-shot gun, it is thus possible to fire 5 charges per trip into the hole.

Comparative results of a single shot and of 8 simultaneous shots are shown in Figure 7. Whereas the single shot at 4,372 ft resulted in a first arrival which was very difficult to pick, the 8 shots gave a strong first arrival. With increasing depth, the strength of the first arrival signal dropped off rapidly; nevertheless, results were obtained to a depth of 8,000 ft, in this case the approximate Upper-Lower

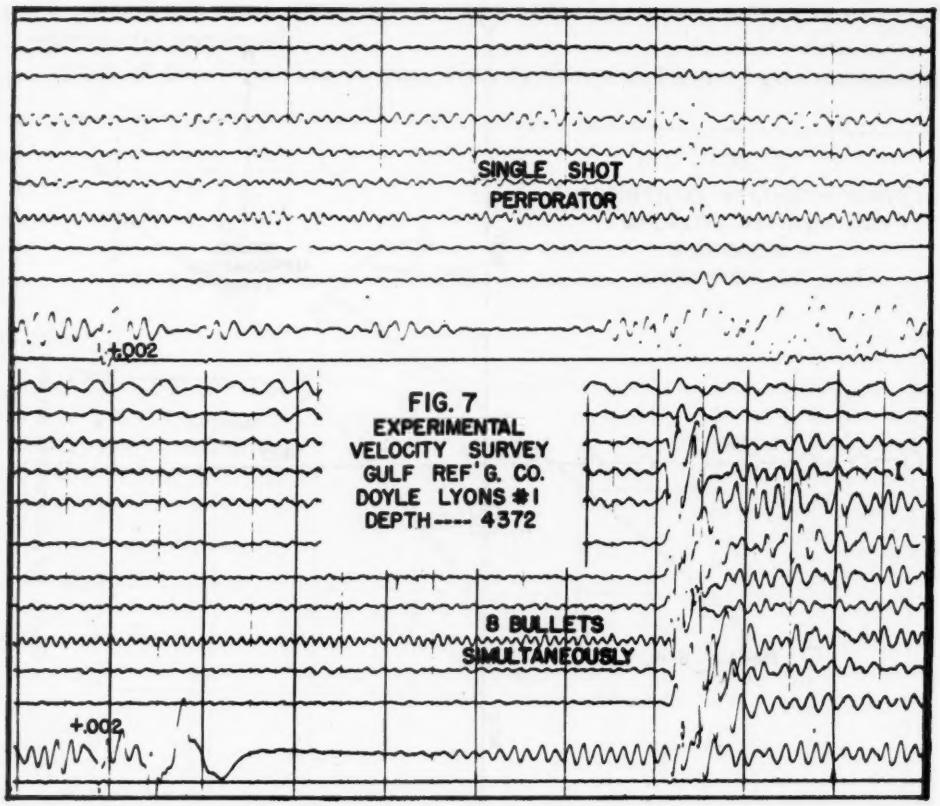

FIG. 7. One shot vs. 8 shots.

Cretaceous contact. Figure 8 shows the vertical travel time and the average velocity curves. The results are quite similar to those obtained in a conventional velocity survey of a well a few miles away.

In the course of this experiment, lead, steel, and bakelite bullets were fired in succession at the same depth to determine if there is any advantage in a particular type. There was very little difference, if any. Perhaps the bakelite bullets gave slightly stronger first arrivals.

IMPROVED TIME BREAK

In all of the experiments described above, the time break was obtained by induction from the gun firing circuit. At the instant of the firing, the current to

the gun is momentarily interrupted by the disruption of the igniter. The time break thus obtained was not so desirable and distinct as is necessary. In an attempt to overcome this difficulty, a microphone was designed to be attached to the gun. Connections to the surface are provided through separate cable conductors. The pulse resulting from mechanical action of the microphone at the instant of firing is amplified and recorded as a time break.

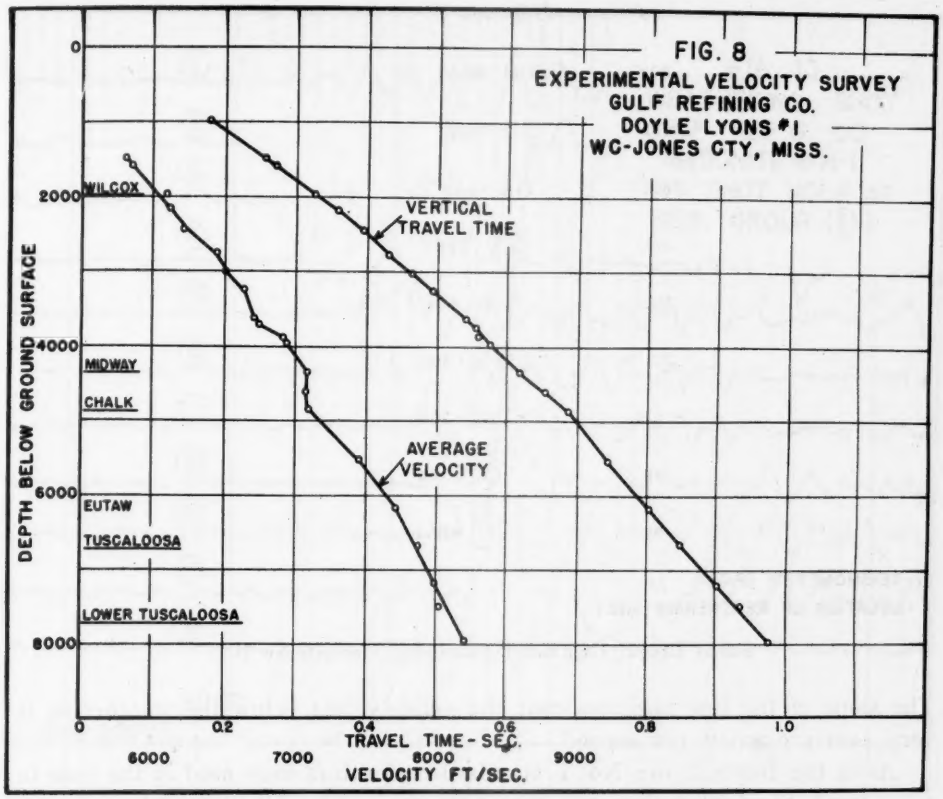

FIG. 8. Curves, Gulf Refining Company Doyle Lyons, No. H-1.

This system was used in the next experiment which took place, in late June, 1951, in the Gulf Refining Company's No. H-1 Masonite, wildcat, Jones County, Mississippi, only a few miles from where the previous experiments were made. The general conditions were similar to those in Gulf's No. 1 Doyle Lyons. Gulf Research Corporation provided the seismic equipment, in this case manufactured by Southwestern Industrial Electronics Company. A sketch of the layout is shown in Figure 9.

WEATHERING DETERMINATION

Seismometers were laid out at 100 ft intervals to 1,000 ft in order to permit making a weathering determination. A small perforator was fired in a 14 ft hand

hole dug at the 200 ft seismometer position. The resulting record is shown in Figure 10. Note the clean character of the time break. From the weathering plot shown in Figure 11, it appears that the hand hole just penetrated the weathering.

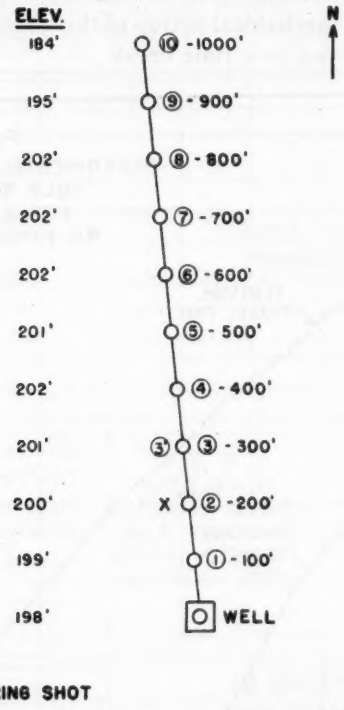

FIG. 9. Layout, Gulf Refining Company Masonite No. H-1.

The slope of the line indicates that the velocity just below the weathering is very nearly 6,000 ft per second.

As in the Doyle Lyons No. 1, standard perforators were used in the hole to total depth. Single shot charges gave results to 4,000 ft while 8 shot charges gave readable results down to the Upper-Lower Cretaceous contact at about 8,660 ft. Excellent time breaks, such as those illustrated on the weathering shot record (Fig. 10), were obtained on virtually every shot.

Various methods of connecting and arranging the surface seismometers were tried. It was concluded that the best results were obtained when the 8 surface seismometers in a given group were separated from each other by some distance, e.g., 10 feet. Also a series connection was found to be better than the parallel or multiple connection.

PRIMACORD EXPLOSIVE

One further step was made in the course of this experiment to develop a stronger explosive for use in the hole. A 20 ft length of primacord was fastened

to an old piece of cable and lowered to a depth of 1,900 ft where it was exploded electrically by means of an insulated blasting cap. The resulting record is compared in Figure 12 to the record obtained at the same depth of 1,900 ft with the single shot perforator. The vastly greater energy of the primacord is quite apparent. Multiple primacord shots could be arranged without difficulty and thus

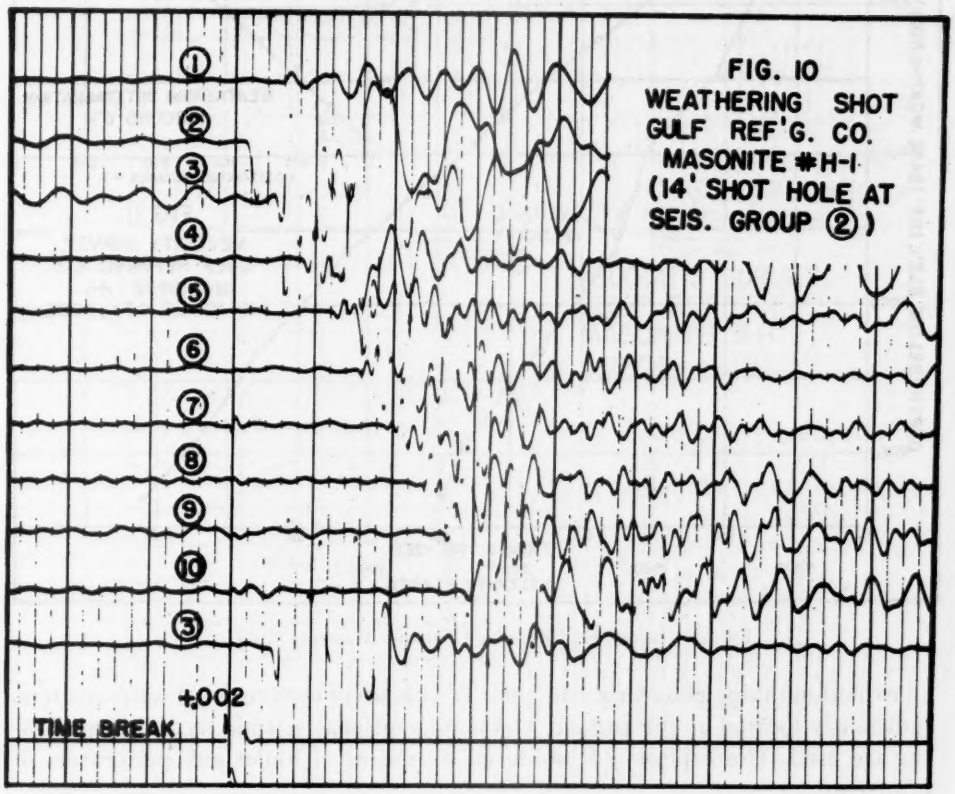

FIG. 10. Weathering shot.

there is a good possibility that this form of explosive could be the solution to the problem of obtaining velocity results to depths of 10,000 ft or more.

The next to the bottom trace on each record in Figure 12 was connected to a seismometer attached to the casing head. Note the strong early arrival via the casing on the lower record. However, surface seismometers as little as 100 ft from the well evidently are unaffected by the casing.

SUMMARY

Several field tests have been carried out recently of a new method for the determination of the seismic velocities of the formations. The method consists essentially of recording at the surface the impact of the seismic wave created by

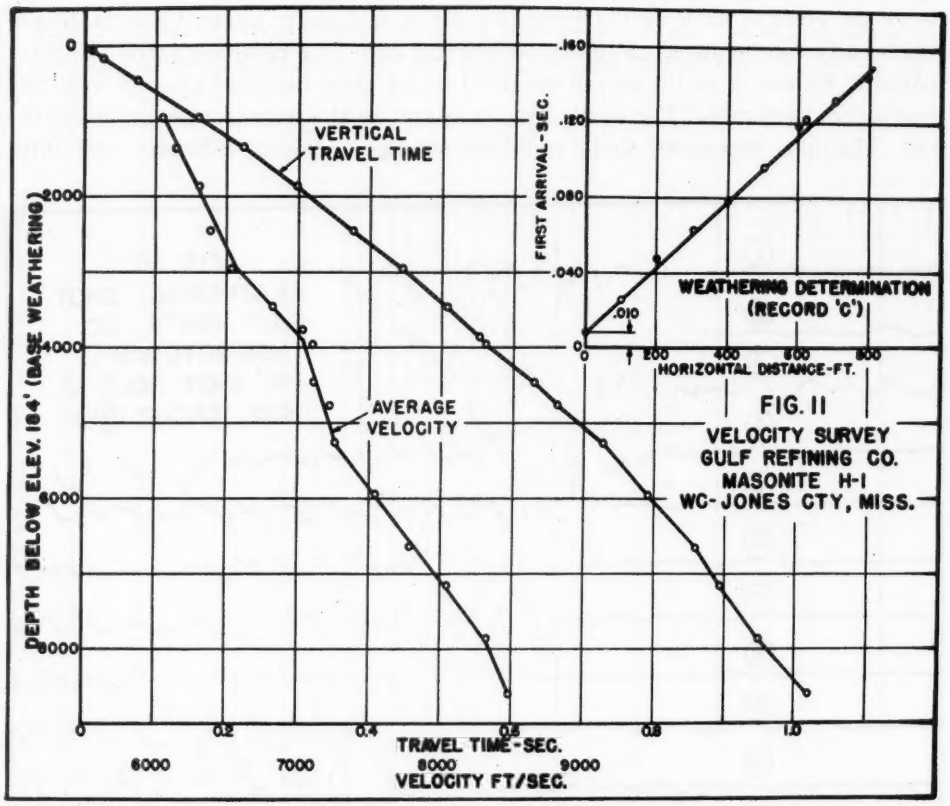

FIG. 11. Curves, Gulf Refining Company Masonite No. H-1.

an explosion taking place in a drill hole. To this effect conventional seismometers, judiciously located at the surface, and a conventional seismic recording apparatus are used. The explosion is produced by means of bullet gun perforators or primacord.

This new method appears to be as accurate as the method used at present, and has, furthermore, the advantage of greater speed, more convenience, and most probably, lower costs.

The various surveys of a bore hole, for example: electrical logs, gamma ray logs, dipmeters, etc., are all geophysical methods; but these have in the past been largely the province of the geologist. With increasing recognition of the importance of seismic velocities, improved velocity surveying methods may very well result in velocity surveys becoming as commonplace as some of the other types of surveys mentioned above. The mutual interest of geologists and geophysicists in seismic velocities can thus become an important factor in promoting cooperation and efficiency in pursuing the common objective of finding more oil.

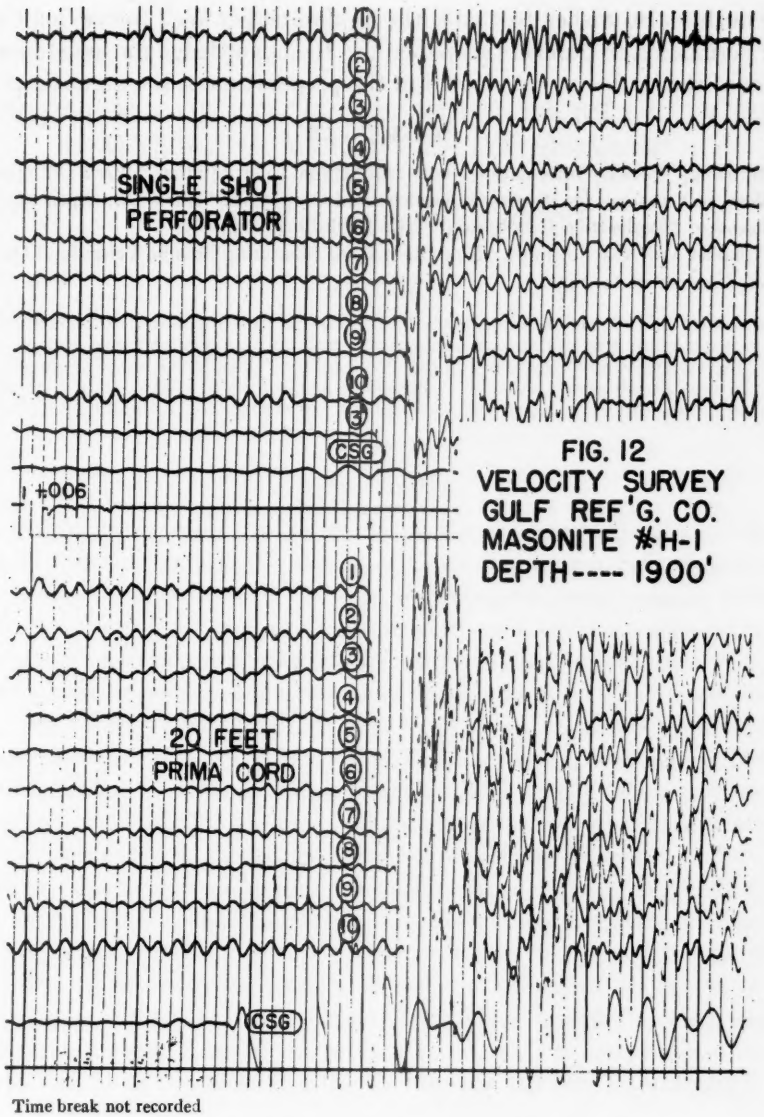

FIG. 12. Perforator vs. Primacord.

ACKNOWLEDGMENT

The author wishes to acknowledge the kind cooperation of The California Company, The Atlantic Refining Company, The Gulf Refining Company, and The General Geophysical Company in making the various experiments, and their courtesies in releasing the data.

The author also wishes to thank the Schlumberger Well Surveying Corporation for permission to publish this paper and to acknowledge the assistance of the members of the staff who have aided in the preparation of the manuscript.

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COMPARISON OF VELOCITIES OBTAINED BY DELTA-TIME ANALYSIS AND WELL VELOCITY SURVEYS*

B. G. SWAN AND ADRIAN BECKER†

ABSTRACT

A comparison of time-depth curves obtained by statistical analysis of delta-times with similar curves from well velocity surveys is presented, representative of results of a study made at a total of 21 wells located in Texas, Oklahoma, Louisiana, Mississippi, Nebraska, and North Dakota. A method applicable to routine studies of delta-times is described. A conclusion is drawn that with average quality reflection data an accuracy of 2 to 3 percent in velocities so obtained may be expected.

INTRODUCTION

An empirical approach to the study of the accuracy of seismic velocity as obtained from the statistical analysis of delta-times from reflection profiles is offered through comparison of the data obtained with well velocity surveys at common locations. Such a study was initiated on a limited scale by the senior author in 1944 and brought up-to-date in 1951 by the junior author. Data used were from routine seismic reflection projects, portions of which coincided with the location of deep wells in which well velocity surveys had been made. The entire study covers areas in Texas, Oklahoma, Louisiana, Mississippi, Nebraska, and North Dakota, and includes comparisons at 21 wells. Though many more such comparisons would be necessary to justify any conclusive statements, representative results of this study are thought to be of interest.

In many of the areas selected, the seismic survey was of sufficient size and density of control to permit studying the effect of progressively increasing the number of spreads used. The area encompassed by each analysis was centered around the well as nearly as possible, in order to minimize the effects of strong lateral velocity and structural gradients. Continuous reversed spreads were used on all projects; spread lengths varied from 1,300 to 2,700 feet, but were not permitted to vary over 200 feet from the average for any one determination.

METHOD OF COMPUTATION

In order to facilitate the handling of the large mass of data required in a statistical delta-T analysis velocity determination, a system is desirable for routine tabulation and assembly of the observed data. Such a system is described briefly for the purpose of indicating some short-cuts which may be taken over that of a rigid computational procedure, and which were used in the preparation

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TABULATIONS FOR ΔT ANALYSIS OF VELOCITIES

SHOTPOINTS	X	E_S	.35	.40	.45	.50	.55	.60	.65
41 – 42	1820	1796	n / ΔT		1 / -70	2 / 133		1 / 65	2 / 120
42 – 43	1770	1810				2 / 122	2 / 118	1 / 62	3 / 155
43 – 44	1800	1804			2 / 131	2 / 125	1 / 58		3 / 143
44 – 45	1810	1801			2 / 133	3 / 215	1 / 67	2 / 115	2 / 110
45 – 46	1800	1795			1 / 63	2 / 112	1 / 56	2 / 108	1 / 49
46 – 47	1820	1812			1 / 72	2 / 140			3 / 135
n' 6	ΣX 10820	ΣE_S 10818	N / ΣΔT		7 / 469	13 / 847	5 / 299	6 / 350	14 / 712

FIG. 1

ΔT ANALYSIS ASSEMBLY AND COMPUTATION SHEET

AREAL UNIT	n'	X	ΣE_S	.35	.40	.45	.50	.55	.60	.65
1	6	10820	10818	N / ΣΔT		7 / 469	13 / 847	5 / 299	6 / 350	14 / 712
2	20	36160	36370			21 / 1399	12 / 808	14 / 868	6 / 316	9 / 421
3	11	19470	20284			6 / 364	25 / 1517	14 / 795	4 / 218	3 / 138
4	20	35170	36680			23 / 1483	22 / 1415	8 / 473	4 / 197	16 / 726
Σn' 57	ΣX 101620	ΣE_S 104152		ΣN / ΣΔT		57 / 3715	72 / 4587	41 / 2435	20 / 1081	42 / 1997
Xave 1783		E_S ave 1827								
$(Xave)^2$ 3179089			ΣN / ΣΔT			129 / 8302	113 / 7022	61 / 3516	62 / 3078	
ΔTave						0644	0621	.0576	.0496	
t_{E_S}						007	007	.007	.007	
1/2 $(tm_1 + tm_2)$				.350	400	.450	.500	.550	.600	
CORRECTION (CHART #1 S2300)						+003	-.007	-.010	+.009	
CHECK COLUMN USED			To			.460	.500	.547	.616	
FORMULA #1 T_2	FORMULA #2 Tave	CHART #				524	.562	.605	.666	

FIG. 2

of data for this paper. The system was developed for regular routine use on field crews in making current velocity studies during the course of a seismic survey.

In this procedure, the normal step-out times, or delta-T's, are read from seismic time cross sections, on which total times for both near and far reflection paths have been plotted and recorded on tabulation sheets. Figure 1 shows part of a sample tabulation sheet. Each horizontal line on this form represents the

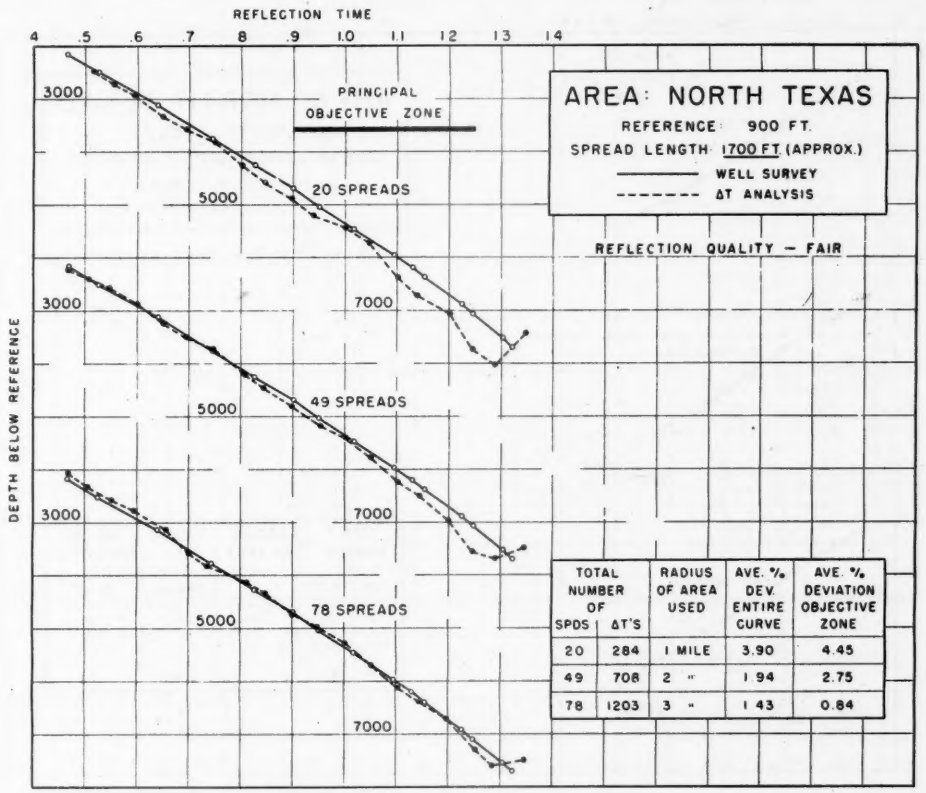
REFLECTION TIME
4 .5 .6 .7 .8 .9 1.0 1.1 1.2 1.3 1.4
DEPTH BELOW REFERENCE
3000
5000
7000
PRINCIPAL OBJECTIVE ZONE
20 SPREADS
49 SPREADS
78 SPREADS
AREA: NORTH TEXAS
REFERENCE 900 FT.
SPREAD LENGTH 1700 FT (APPROX.)
WELL SURVEY
ΔT ANALYSIS
REFLECTION QUALITY — FAIR
TOTAL NUMBER OF SPDS | ΔT'S
RADIUS OF AREA USED
AVE. % DEV. ENTIRE CURVE
AVE. % DEVIATION OBJECTIVE ZONE
20 | 284 | 1 MILE | 3.90 | 4.45
49 | 708 | 2 " | 1.94 | 2.75
78 | 1203 | 3 " | 1.43 | 0.84

FIG. 3

normal delta-T's from one reversed spread. The delta-T's are grouped in 50 millisecond zones; the number of observations in the zone is entered in the upper left corner of the square; the total, or summation delta-T in milliseconds, is placed in the lower right corner. In the normal procedure, one tabulation sheet is used for a small areal unit such as a square mile, which facilitates combination in any manner desired. Totals from these sheets are transferred to an assembly and computation sheet (Fig. 2); each line on this form represents the totals from one tabulation sheet. As a smoothing process, totals from the 50 millisecond zones are overlapped into 100 millisecond zones (e.g., the zones .500 to .550

second and .550 to .600 second are combined to form the zone .500 to .600 second; the zones .550 to .600 second and .600 to .650 second are combined to form the zone .550 to .650 second, etc.) and an average delta-T is determined for each overlapped zone. The line labeled t_{E_s} is a correction applied to convert the reflection times, which are originally based on the elevation reference chosen for the project, to a new reference which is the average shot elevation of all the spreads used

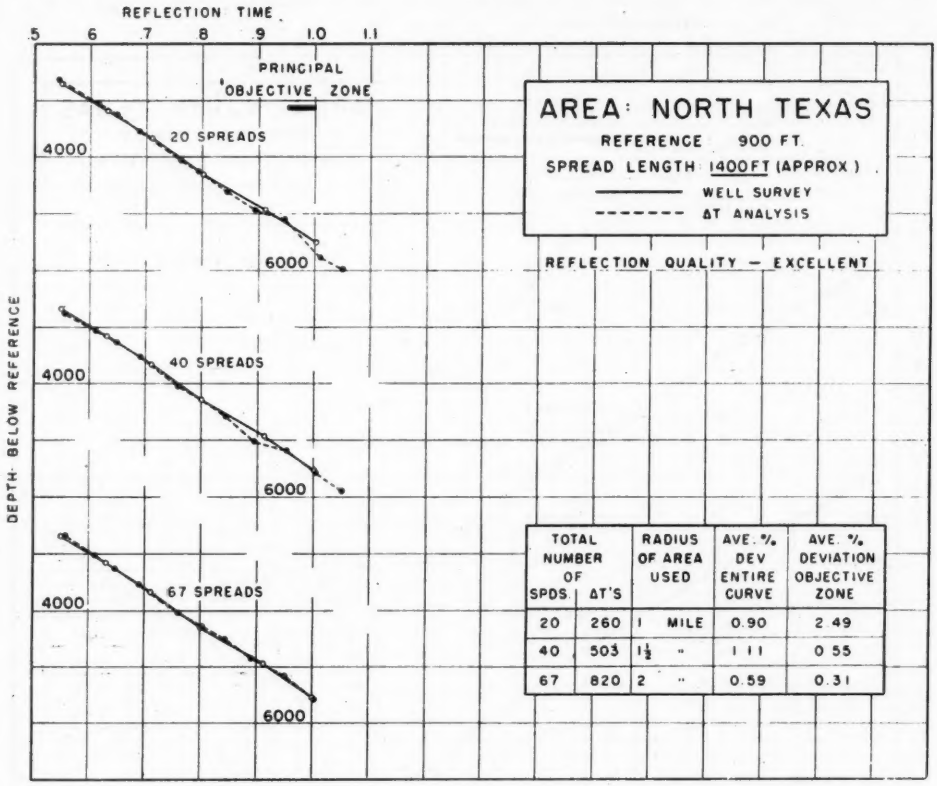
REFLECTION TIME
.5 .6 .7 .8 .9 1.0 1.1
PRINCIPAL OBJECTIVE ZONE
20 SPREADS
40 SPREADS
67 SPREADS
4000
6000
DEPTH BELOW REFERENCE
AREA: NORTH TEXAS
REFERENCE 900 FT.
SPREAD LENGTH 1400 FT (APPROX.)
WELL SURVEY
ΔT ANALYSIS
REFLECTION QUALITY — EXCELLENT
TOTAL NUMBER OF SPDS. | ΔT'S | RADIUS OF AREA USED | AVE. % DEV ENTIRE CURVE | AVE. % DEVIATION OBJECTIVE ZONE
20 | 260 | 1 MILE | 0.90 | 2.49
40 | 503 | 1½ " | 1.11 | 0.55
67 | 820 | 2 " | 0.59 | 0.31

FIG. 4

in the velocity determination. This makes the reflection total times more representative of the same physical conditions as those under which they were observed. The next line labeled $\frac{1}{2}(t_{m1}+t_{m2})$ is simply the midtime for each zone (e.g., .550 for the zone .500 to .600 second). The line labeled "correction" is determined by a weighted average of the number of observations in each of the 50 millisecond zones which make up the overlapped 100 millisecond zone. This serves to shift the midtime to make it applicable to the specific zone, and thus obviates the need for recording the near time of each reflection. In the case where both of the 50 millisecond zones making up the overlapped zone have the same number of observations or delta-T's, this correction would, of course, be zero. T_0 is the cor-

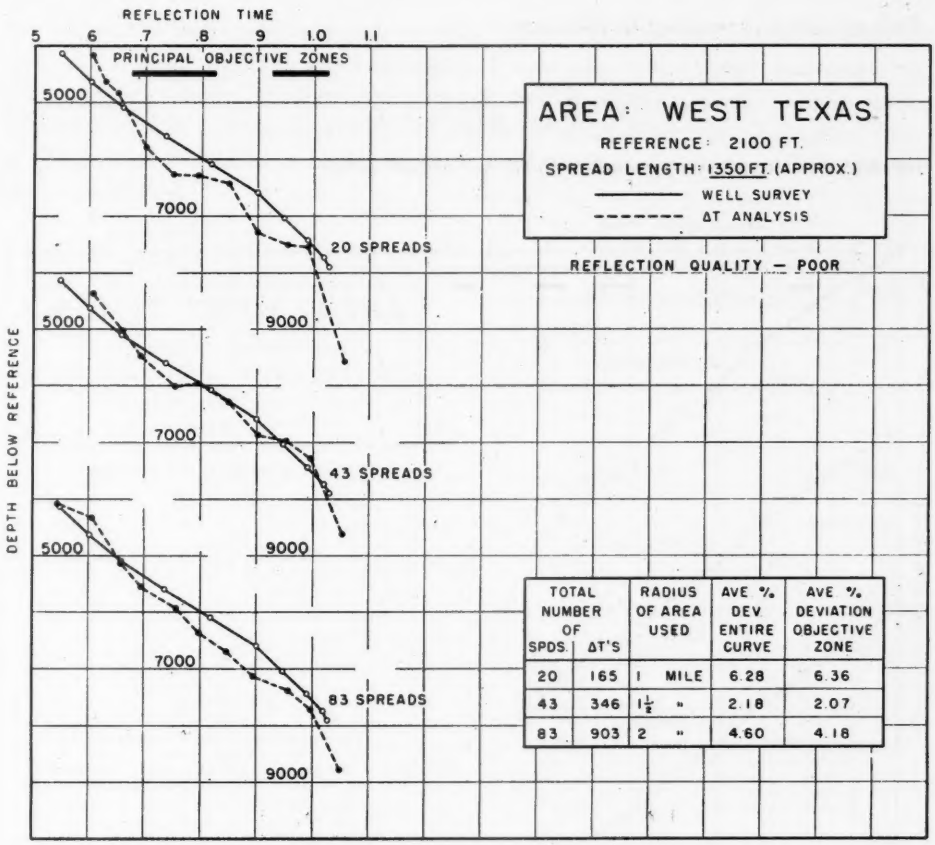
REFLECTION TIME
5 6 .7 .8 9 1.0 1.1
PRINCIPAL OBJECTIVE ZONES
DEPTH BELOW REFERENCE
5000
7000
9000
20 SPREADS
43 SPREADS
83 SPREADS
AREA: WEST TEXAS
REFERENCE: 2100 FT.
SPREAD LENGTH: 1350 FT. (APPROX.)
WELL SURVEY
ΔT ANALYSIS
REFLECTION QUALITY – POOR
TOTAL NUMBER OF SPDS. | ΔT'S | RADIUS OF AREA USED | AVE % DEV. ENTIRE CURVE | AVE % DEVIATION OBJECTIVE ZONE
20 | 165 | 1 MILE | 6.28 | 6.36
43 | 346 | 1½ " | 2.18 | 2.07
83 | 903 | 2 " | 4.60 | 4.18

FIG. 5

rected reflection time for the zone to the near receptor ($T_0 = \frac{1}{2}(t_{m1} + t_{m2}) \pm t_{E_s} \pm$ correction). T_2 is the corrected reflection time to the far receptor ($T_2 = T_0 + \Delta T_{ave}$). The balance of the form not shown on Figure 2 consists of a few simple steps to obtain the average velocity from the general velocity formula:

$$V^2 = \frac{X_2^2 - X_1^2}{T_2^2 - T_1^2}$$

where

X_2 = distance of far receptor from the shot
X_1 = distance of near receptor from the shot
T_2 = reflection time of far receptor
T_1 = reflection time of near receptor
V = effective velocity

This equation is reduced to the form:

$$V^2 = \frac{X^2}{\Delta T(T_2 + T_0)}$$

for use with reversed spreads where X_1 equals zero.

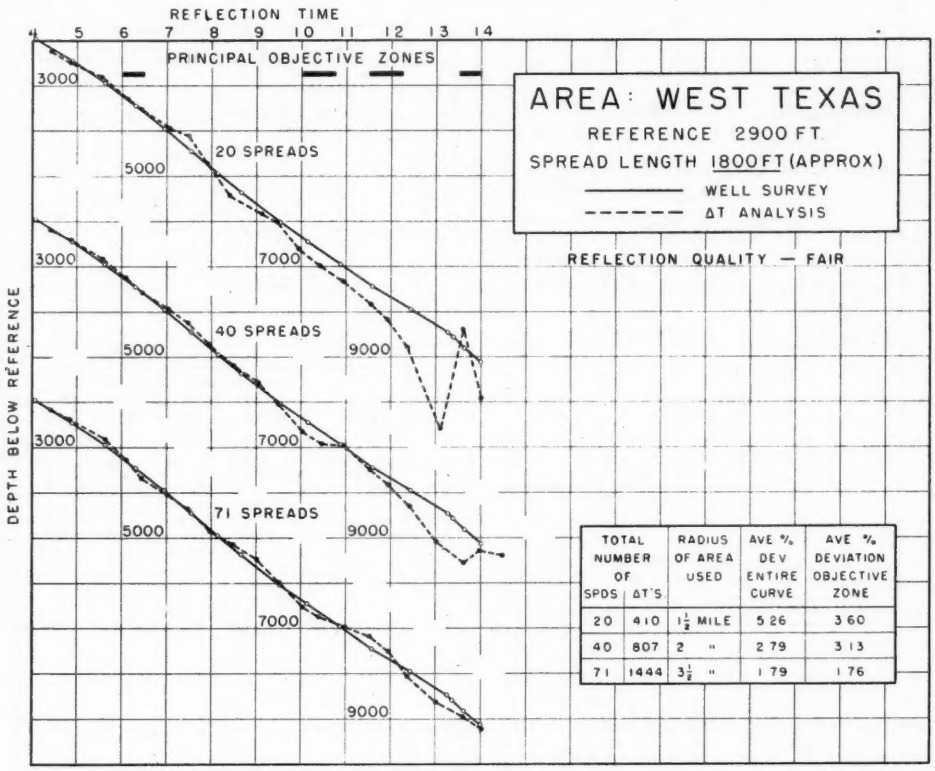
REFLECTION TIME
4 5 6 7 8 9 10 11 12 13 14
PRINCIPAL OBJECTIVE ZONES
DEPTH BELOW REFERENCE
3000
5000
7000
9000
20 SPREADS
40 SPREADS
71 SPREADS
AREA: WEST TEXAS
REFERENCE 2900 FT.
SPREAD LENGTH 1800 FT (APPROX)
WELL SURVEY
ΔT ANALYSIS
REFLECTION QUALITY — FAIR
TOTAL NUMBER OF SPDS | ΔT'S
RADIUS OF AREA USED
AVE % DEV ENTIRE CURVE
AVE % DEVIATION OBJECTIVE ZONE
20 | 410 | 1½ MILE | 5 26 | 3 60
40 | 807 | 2 " | 2 79 | 3 13
71 | 1444 | 3½ " | 1 79 | 1 76

FIG. 6

PROCEDURE

The procedure followed in making the comparisons consisted of a common plotting of the time-depth curves from the well survey and delta-T analysis as in Figures 3, 4, 5, 6, 7, 8, and 9, but to a larger scale which allowed high reading accuracy. Depths were recorded from both curves at 25 millisecond intervals and the deviations of the delta-T analysis curve from the well survey in feet and percent computed. If the well survey time-depth curve is assumed to give the correct velocity in each case, then these deviations may be considered as being representative of the errors involved. However, it should be remembered that at least part of this apparent error in the delta-T curves may be due to imper-

fections in the well surveys, which are also subject to error, but of smaller magnitude than might be expected from delta-T analysis. No attempt was made to draw smooth curves through the delta-T points, since it was thought more desirable to study the accuracy of the unaltered data. However, it is noted that in the majority of cases, a better fit with the well survey is obtained if a smooth curve is drawn.

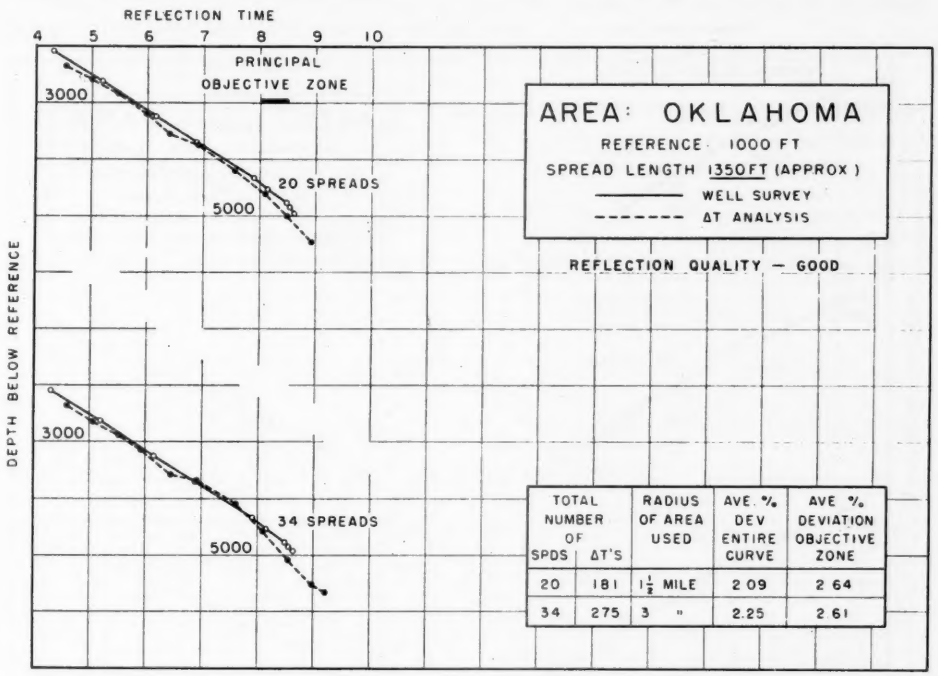

FIG. 7

RESULTS

The results of this study are shown in Figures 3, 4, 5, 6, 7, 8, and 9 which are representative, from the standpoint of accuracy of data and geographical location, of the comparisons made at all 21 wells. The objective zones referred to on the figures are time zones which were considered to have the most geological significance for the specific project. The table in the lower right corner of each figure gives the number of spreads used for each analysis, number of delta-T's, approximate radius of area used, average percent deviation over the entire curve, and the average percent deviation within the objective zone.

Figures 3, 5, 6, and 8 are examples taken from areas of poor to fair or average record quality. Figures 4, 7, and 9 are examples taken from areas of good to excellent record quality. Figure 5 is a special case presented to show what can happen when the spreads used in the determination are not centered around the

well. This is especially important in areas such as West Texas where the lateral velocity gradients may be severe. The analysis using 43 spreads (middle curve on the figure) was centered around the well, and its time-depth curve is noted to follow the well velocity time-depth curve reasonably well. The other two delta-T analyses, however, had the bulk of their spreads to the west of the well in the direction of higher regional velocities. The effect of this is found on both the

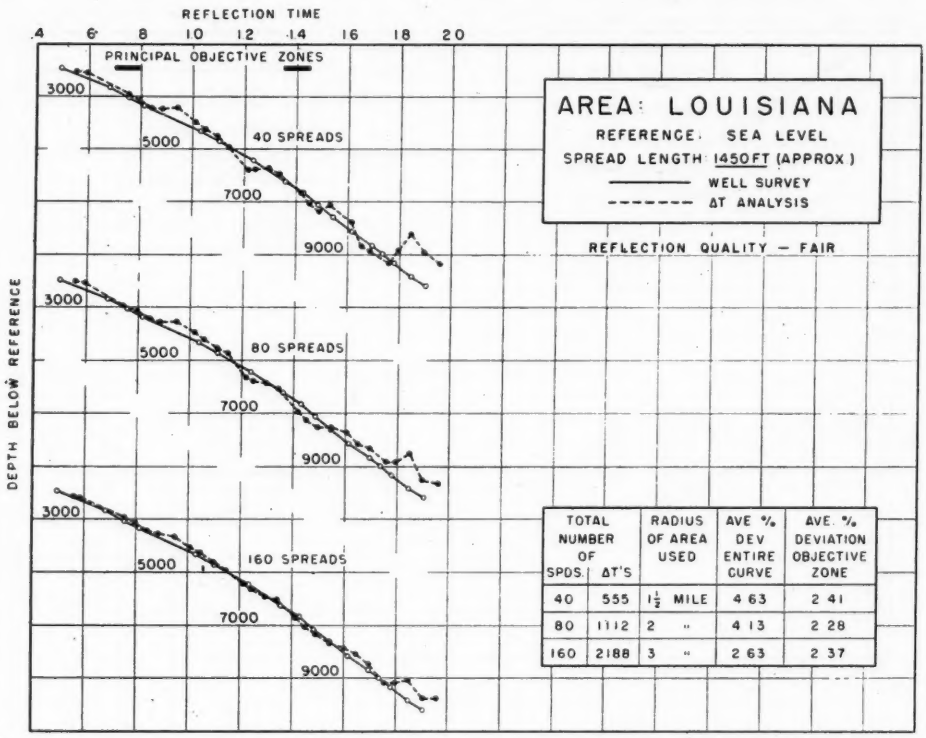
REFLECTION TIME
4 6 8 10 12 14 16 18 20
PRINCIPAL OBJECTIVE ZONES
DEPTH BELOW REFERENCE
3000
5000
7000
9000
40 SPREADS
80 SPREADS
160 SPREADS
AREA: LOUISIANA
REFERENCE: SEA LEVEL
SPREAD LENGTH 1450 FT (APPROX.)
WELL SURVEY
ΔT ANALYSIS
REFLECTION QUALITY — FAIR
TOTAL NUMBER OF SPDS. | ΔT'S | RADIUS OF AREA USED | AVE % DEV ENTIRE CURVE | AVE % DEVIATION OBJECTIVE ZONE
40 | 555 | 1½ MILE | 4 63 | 2 41
80 | 1112 | 2 " | 4 13 | 2 28
160 | 2188 | 3 " | 2 63 | 2 37

FIG. 8

upper and lower delta-T time-depth curves by the consistently higher velocities they indicate.

Figure 10 is a graph with percent deviation plotted versus number of delta-T's. The deviation from the well curve in percent was found for each computed point on the delta-T time-depth curves, and this value plotted against the number of delta-T's at the point in each case. The curve shown is an average drawn through the points which represent data from the entire 21 areas studied. The percent deviation is noted to decrease at a fairly uniform rate, falling below 2 percent in the neighborhood of 180 delta-T's. However, since a number of these comparisons were from areas which would ordinarily have been classified as unsuitable for this type of data, this curve does not give an entirely true picture

of the accuracy to be expected in normal application of the method. A somewhat better curve is obtained when the data from these areas are removed, the percent deviation falling below 2 percent in the neighborhood of 120 delta-T's. Of course, in good reflection areas, considerably fewer than 120 delta-T's per point can often be used and still retain an accuracy within 2 percent. Likewise, in very poor reflection areas, even an extremely large number of delta-T's may not produce very accurate or even usable data.

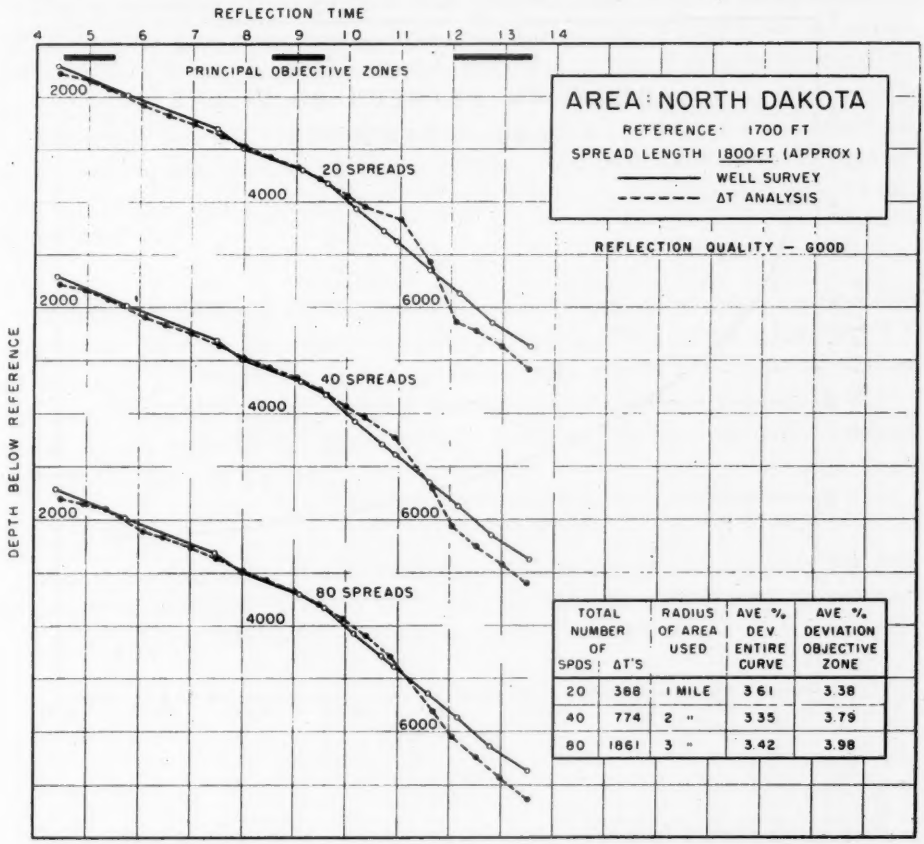
REFLECTION TIME
4 5 6 7 8 9 10 11 12 13 14
PRINCIPAL OBJECTIVE ZONES
DEPTH BELOW REFERENCE
2000
4000
6000
20 SPREADS
40 SPREADS
80 SPREADS
AREA: NORTH DAKOTA
REFERENCE 1700 FT
SPREAD LENGTH 1800 FT (APPROX.)
WELL SURVEY
ΔT ANALYSIS
REFLECTION QUALITY – GOOD
TOTAL NUMBER OF SPDS | ΔT'S | RADIUS OF AREA USED | AVE % DEV ENTIRE CURVE | AVE % DEVIATION OBJECTIVE ZONE
20 | 388 | 1 MILE | 3.61 | 3.38
40 | 774 | 2 " | 3.35 | 3.79
80 | 1861 | 3 " | 3.42 | 3.98

FIG. 9

DISCUSSION

There are a number of factors that affect the accuracy and utility of velocities determined by the statistical analysis of delta-T's. Five of these are, somewhat in order of importance, as follows:

1. Quality of reflections
2. Number of spreads (or delta-T's)
3. Spread length

4. Distribution of reflections
5. Size of area

The relative importance of reflection quality and number of spreads on the accuracy of a delta-T analysis can be demonstrated from the preceding figures. Referring to Figures 4, 7, and 9 from areas of high record quality, it will be noted that the percent deviation did not drop appreciably when more spreads were used. In most of these areas, even a small number of spreads produced delta-T

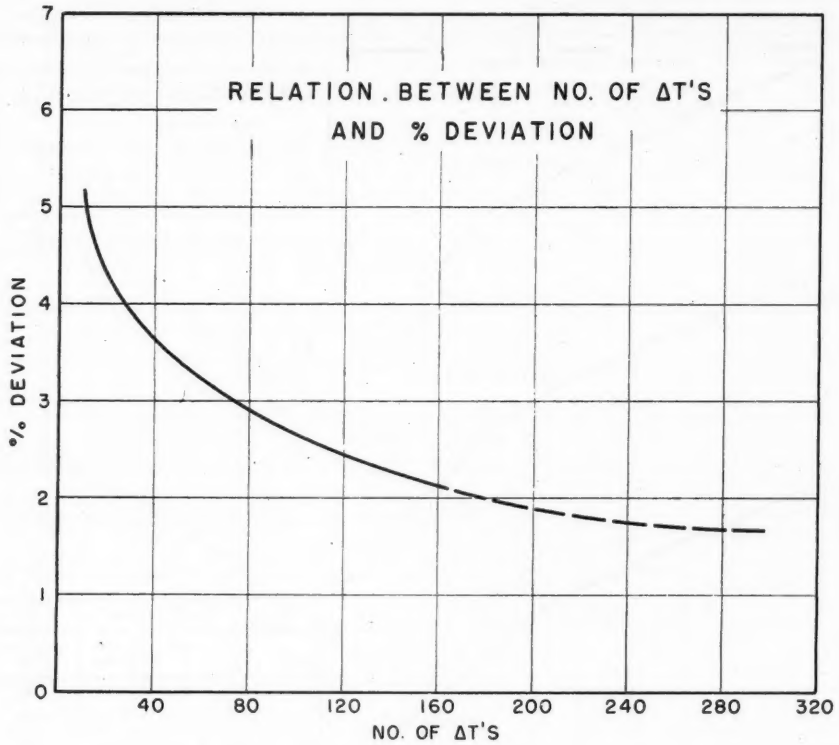

FIG. 10

curves which closely fitted the well velocity curves. However, in areas of fair or average record quality (Figures 3, 6, and 8), usually a consistent decrease in percent deviation was noted with the use of additional spreads. In other words, it was necessary to use a larger quantity of observations to overcome, to a certain extent at least, the lower quality of the data.

No tendency was found for velocities from delta-T analyses to be consistently higher or lower than those obtained from well velocity surveys in the areas covered by this study and using spread lengths within the limits of 1,300 to 2,700 feet. Also, no direct relationship could be established between spread lengths and the resulting accuracy of the determination.

The distribution of reflections affects the ability of the delta-T analysis to show the velocity stratification in the geologic section. This factor often depends to a great extent on the thoroughness with which the records are picked. A good deal of valuable information can be lost by picking only reflections used for correlations rather than picking all reliable reflections on the records. The number of delta-T's per spread is also increased by this practice, thus allowing fewer spreads and consequently, less area to be used for each analysis.

The areal extent of the analysis is of greatest importance in areas of strong lateral velocity gradients. Special care chould be taken in such cases to center the spreads as nearly as possible around the point at which velocity information is desired.

Two other factors, not thought to be represented in any of these examples to any extent, are those of multiple reflections and path angularity. These factors, however, should be considered in any treatment of delta-time velocity determinations.

CONCLUSIONS

Because of the many factors involved, it is difficult to establish any definite relationship between the number of spreads or delta-T's and the reliability of a delta-T analysis. However, from the comparisons made to date, it seems reasonable to conclude that in average reflection areas, by using in the neighborhood of 100 to 120 delta-T's per point (usually 50 to 60 spreads), delta-T velocities accurate within 2 to 3 percent can be expected.

ACKNOWLEDGEMENTS

We wish to express our gratitude to the Continental Oil Company for permission to publish this paper, to Mr. John Crawford for his help and suggestions, and to Mr. Ralph Adams for preparation of the illustrations.

A SEISMIC VELOCITY LOGGING METHOD*

C. B. VOGEL†

ABSTRACT

A well logging method is described which measures seismic velocity as a function of depth. The method uses a transient sound pulse, thus making possible the resolution of shear waves. Various systems of sources and receivers for minimizing bore hole errors are discussed. With the most elaborate system considerable accuracy is obtainable in the face of large bore hole diameter variations.

The seismic velocity logging method here described was developed as a counterpart to acoustic methods using continuous waves. The method uses a transmitter, capable of producing discrete sound pulses within the borehole, and associated receivers and recording equipment for observing the various waves excited. It is thus a transient method of measurement which allows the resolution of various types of sound waves propagated within the borehole. Such resolution is not easily accomplished with continuous waves, especially where it is desired to use a small measuring interval for good resolution of thin layers. With a transient method it is possible to measure the compressional and shear wave velocities of rocks, and in some types of rock the existence of the various types of waves results in distinctive oscillographic patterns by which the rock type may be identified. Such distinctive oscillograms may serve, as it were, for a "signature" of the rock.

The instruments used in this method have as a sound source the miniature explosion produced by an electric arc. The arc is obtained by discharging a capacitor through electrodes immersed in a liquid. Such a sound source produces pulses with a rise time of a few microseconds. Under conditions of low hydrostatic pressure, it is possible to obtain instantaneous acoustic output of the order of a megawatt from such sources. However, hydrostatic pressure has the effect of changing the sound pulse from a simple nonoscillatory pulse into a rapidly oscillating one, the period and amplitude of which decrease with increasing pressure. The result is that the effective power of the transmitter decreases about 3 decibels per thousand feet within an oil well. The receivers used consist of piezoelectric, hydrophone-type detectors and electronic amplifiers. The transmitter and receiver are spaced vertically 5 feet apart, separated by an elastic connecting link. As the instruments are lowered into a well, the transmitter produces a sound pulse at 5-foot intervals and a simultaneous electrical time-break signal, which is transmitted to the surface by a well logging cable. The receiver output is trans-

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† Shell Oil Company, Houston, Texas.

mitted over the same cable and displayed on a cathode ray oscilloscope, which is continuously photographed, together with the depth of the instrument and timing calibration signals. Thus the record obtained consists of a strip of film across which are printed a series of miniature refraction seismograms and associated

FIG. 1(a). Well instruments.

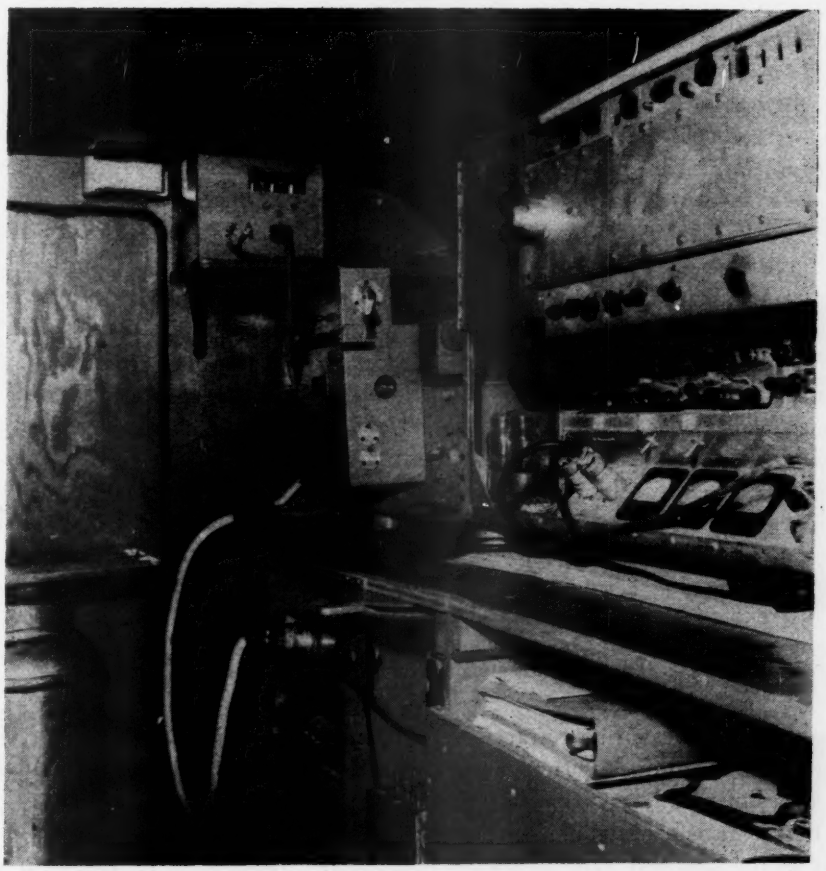


FIG. 1(b). Surface recording and control instruments.

depths. The transmitter-receiver spacing is sufficiently large that the first pulse received is that refracted by the borehole wall, so that it indicates directly the seismic velocity of the formations tranversed. Figure 1 illustrates the general appearance of the well instrument and the surface recorder.

This type of instrumentation results in considerable error when the bore-

hole-diameter variation is large, because of the time required for the refracted pulse to travel from the transmitter to the borehole wall and from the wall to the receiver. This error is proportional to the cosine of the critical angle between fluid and wall and thus increases with the velocity of the wall. However, if the hole diameter is constant, or the instrument hangs against the wall during traverse of the hole, the error is constant and a reasonable correction can be made for it. These conditions are sometimes met in hard formations. Despite the errors

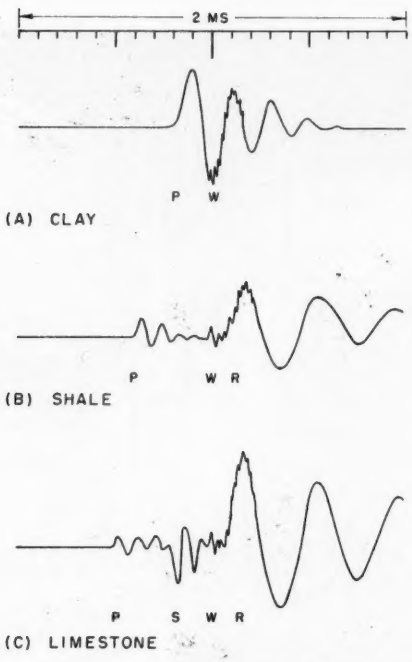


FIG. 2. Drawings illustrating recordings from different types of rocks.

possible when measuring refraction traveltimes with this simple type of instrument, records obtained with it reveal the type of response to be observed in different types of rock.

Figure 2a is a drawing showing the typical features of records made in clay. This is the simplest type of record obtainable, showing at *W* the fluid wave, propagated with the velocity of water, and at *P* the compressional wave propagated through the formation. Owing to higher losses in the drilling mud, shallow measurements in many cases fail to show the high-frequency water wave. The frequency of the compressional wave train is in general below 5,000 cps and goes up with increasing speed of the formation.

Figure 2b similarly illustrates typical features of records obtained in shale. Here, also, the record is quite simple. However, the frequency of the compres-

sional wave train is higher than in the case of clay and does not show a simple relationship to the seismic velocity of the wall. Shear waves, when observed, are small.

Figure 2c, illustrating the type of record obtained in limestone holes, shows the compressional and shear waves *P* and *S*, a fluid wave *W*, and a low-frequency surface wave *R*. The *P*- and *S*-waves have equal frequencies (usually above 10,000 cps) proportional to the velocity of the limestone. The shear wave is always larger than the *P*-wave, though the amplitude ratio of these waves varies from 2 to 5. The surface wave has usually about ten times the amplitude of the *P*-wave and about one-fourth its frequency. The water wave is very small and usually has a frequency above 30 kcs. Limestone is in general characterized by the presence of prominent shear waves. Shales, on the other hand, even with comparable velocities usually do not exhibit shear waves. Where the shear wave is present, it serves as a useful criterion for distinguishing velocity variations from hole effects. This is due to the fact that the time difference between the *P*- and *S*-wave arrivals does not vary with hole diameter.

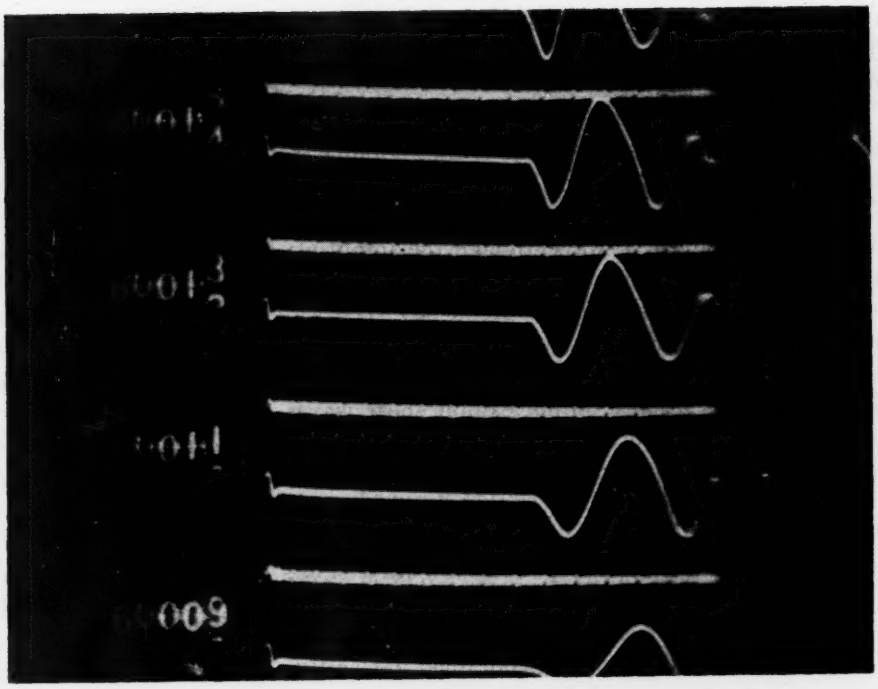
The simple logging instrument described above has been used in numerous shallow holes and several deep wells. Figure 3 shows records obtained in clay, shale, and limestone. Owing to the high-frequency losses in the recording system, the water wave is not easily distinguished.

Figure 4a shows velocity logs obtained in a well to a depth of approximately 6,000 feet in the Flanagan field of West Texas. Alongside the velocity log is shown the resistivity curve. There is a vertical shift between these curves of about 15 feet. Also, a comparison is shown between traveltimes obtained from a conventional seismic velocity survey in a near-by well and the corresponding traveltimes obtained by integrating measurements obtained with the velocity logger. Surface reflection prospecting shows a prominent reflector at 4,150 feet. This is seen to correspond with an increase shown on the velocity log at 4,200 feet.

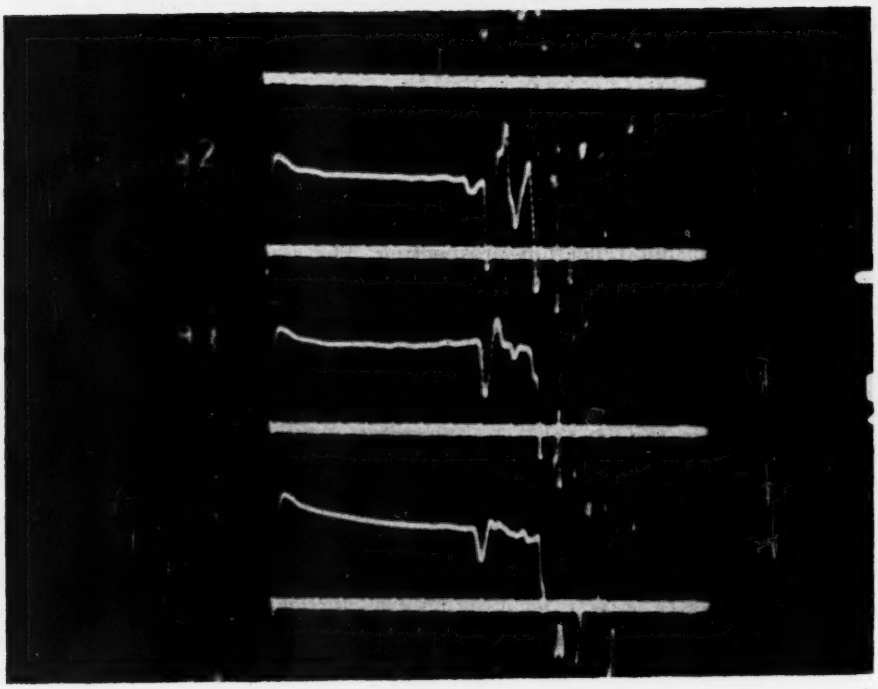
Figure 4b shows a velocity log obtained from a well in the Hare field of New Mexico. Also shown are the resistivity log and the approximate depth of reflectors as obtained by seismic reflection prospecting. The same 15-foot shift exists between the curves. It will be seen that there is fair correlation between the velocity and resistivity logs. Both the *P*- and *S*-wave velocities are shown on the log and, in general, the S-curve excursions are larger than those of the *P*-curve, suggesting that borehole effects are small. Thus it may be assumed that this hole has a rather constant diameter or that the instruments rest against the borehole wall during traverse of the well. Velocity breaks roughly corresponding to reflections are seen at 3,800 feet and 5,100 feet.

Although satisfactory velocity logs are obtainable in good holes with the simple single-receiver logger, this is not true for holes in which there is considerable caving or diameter variation, as is often the case in shales and poorly consolidated sands.

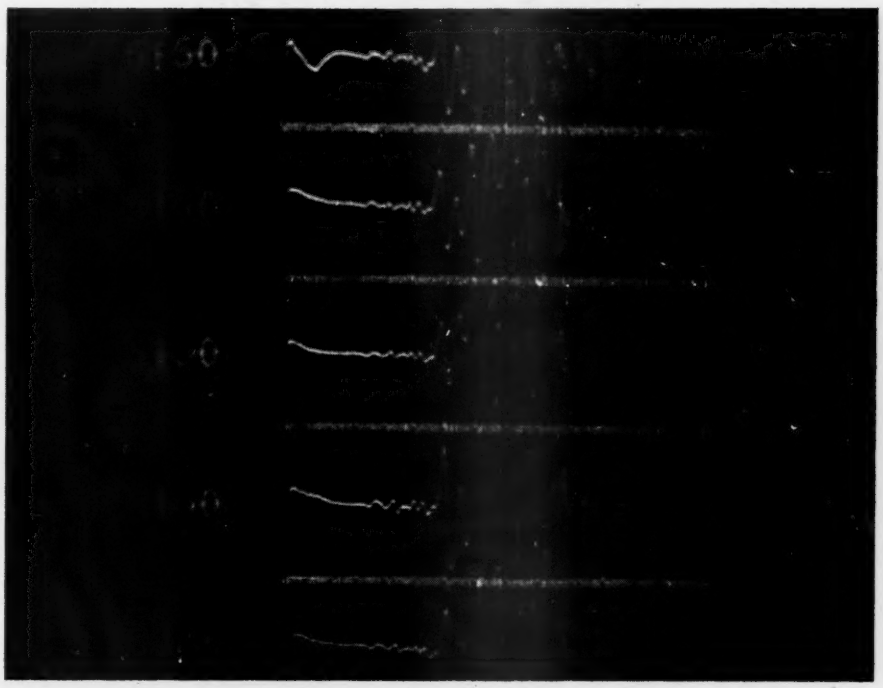
Figure 5 shows velocity and resistivity logs from a well in the North Port



(a) Clay



(b) Shale



(c) Limestone

FIG. 3. Actual records obtained with single-receiver instrument from different types of rocks.

Neches field of Texas. The velocity log is plotted as an envelope which contains the curves obtained from successive traverses of the hole. Two things are obvious: (1) The measurements are not reproducible; (2) there is no correlation with the electric log. Comparison of the logging velocities with those obtained by seismic survey shows that many of the former are far too low and only the maximum values approximate the seismic values. Thus it appears that a more refined technique is required for velocity logging in such holes. An improved instrument with two receivers was constructed in order to obtain more accurate measurements.

Figure 6 shows the type of record obtained with this technique. Here we see the beginning of the record obtainable from the near receiver and all of the record obtainable from the other. This type of instrument reduces the errors obtained in a single measurement. These errors now become proportional to the difference between the distances of the two receivers from the borehole wall rather than proportional to the sum of the distances of the source and receiver from the wall, as in the case of the single-receiver instrument. Errors, though smaller, are still possible. However, if the traveltime values obtained with two receivers are integrated over any considerable distance, the errors tend to cancel in such a way that the error in the intergrated values is equal only to the absolute error of one

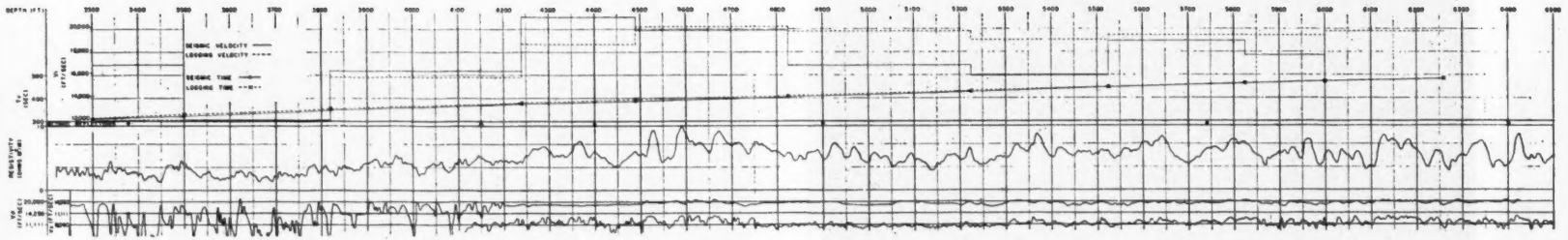


FIG. 4(a). Seismic, electric log and velocity log data—Coates and Lea No. 1.

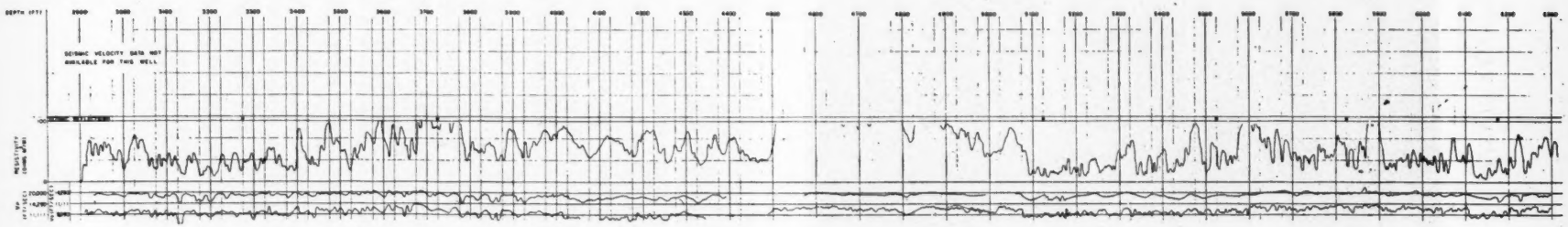


FIG. 4(b). Seismic electric log and velocity log data—Turner No. 8.

measurement. Thus reasonably accurate total-traveltime measurements are obtainable.

Figure 7 shows two-receiver velocity logs with corresponding resistivity curves obtained in several core holes in the Puente Hills of California. It is seen that there

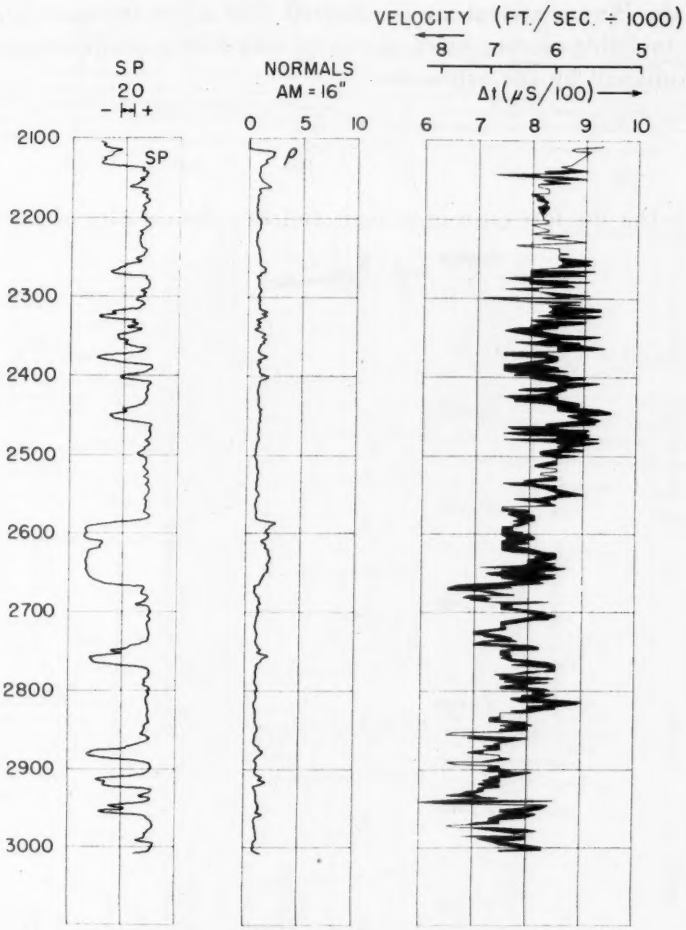


FIG. 5. Velocity and resistivity logs from a well in the North Port Neches Field of Texas.

are numerous small velocity features and that these correlate with the resistivity log.

Figure 8 shows the velocity log, the average velocity obtained therefrom, and the results of seismic measurements in the same hole. Owing to the high attenuation of the sound pulse at shallower depths, no logging values are shown above 1,35 feet.

Although the double-receiver instrument appears to be quite accurate for

obtaining average velocity values, its use still allows considerable errors in the discrete values shown on the log. These can become excessive where there is considerable hole-diameter variation. A more complicated instrument has been constructed to reduce these errors still further.

The accuracy obtainable now becomes dependent chiefly upon the precision with which the *P*-wave arrival can be resolved. The errors are essentially reading errors. The probable reading error of the inception of a compressional wave is give approximately by the expression

$$|E| < \frac{0.1}{V}$$

where $|E|$ is the absolute error in seconds and V is the velocity of the formation

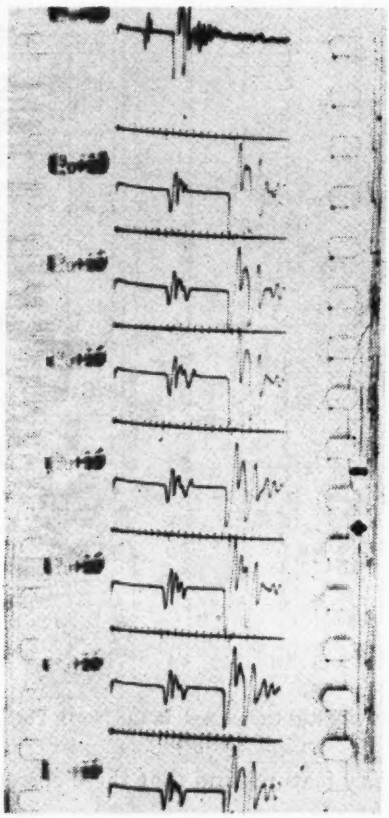


FIG. 6. Records obtained with two-receiver instrument.

in ft/sec. This requires reading a (quasi) sinusoidal wave to one-tenth of a period. This relationship is due to the fact that the frequency of the compressional wave is roughly proportional to the velocity. The probable error for the average of two time differences, when the receivers are 5 feet apart, is thus approximately

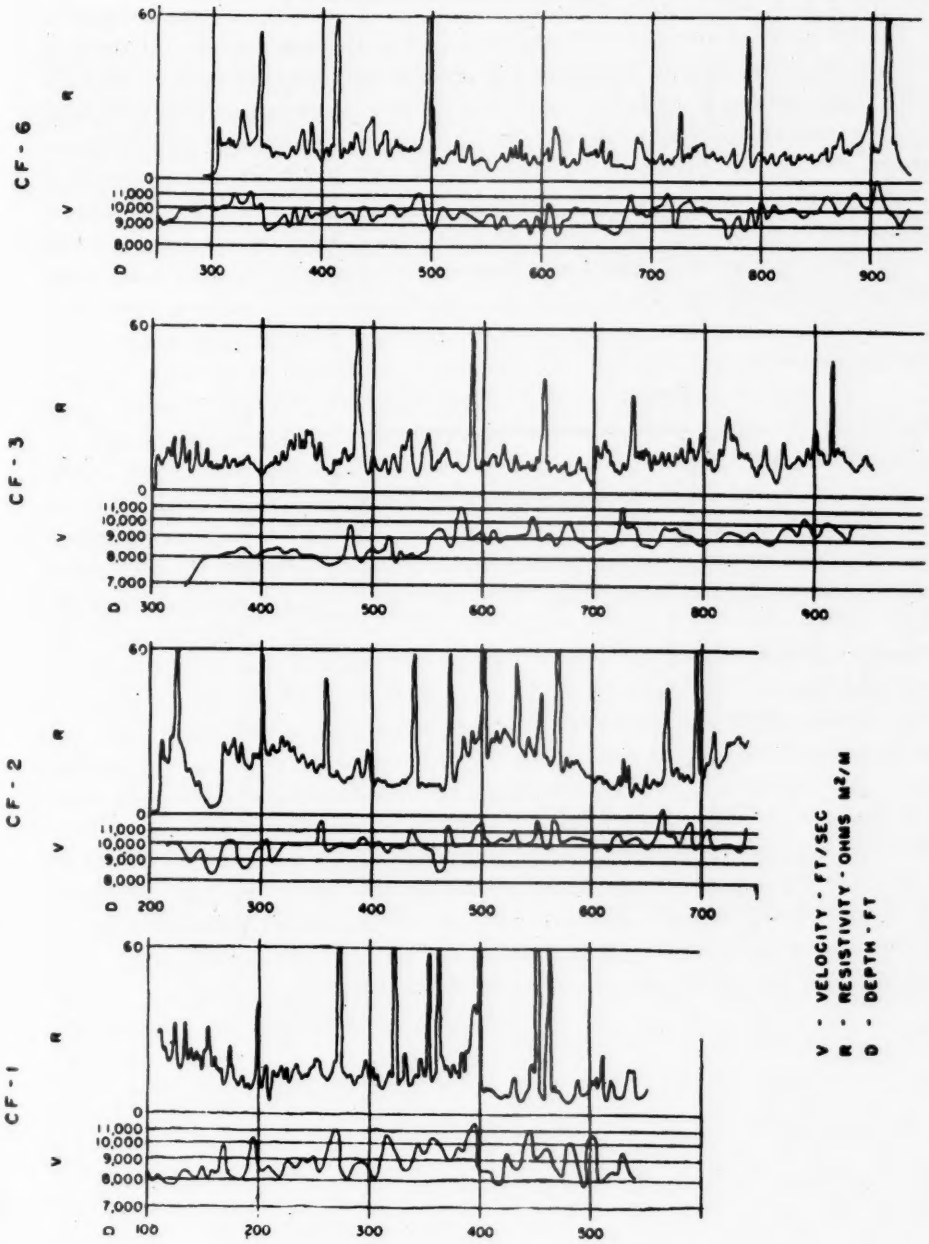


FIG. 7. Velocity logs and corresponding resistivity curves from core holes in the Puente Hills of California.

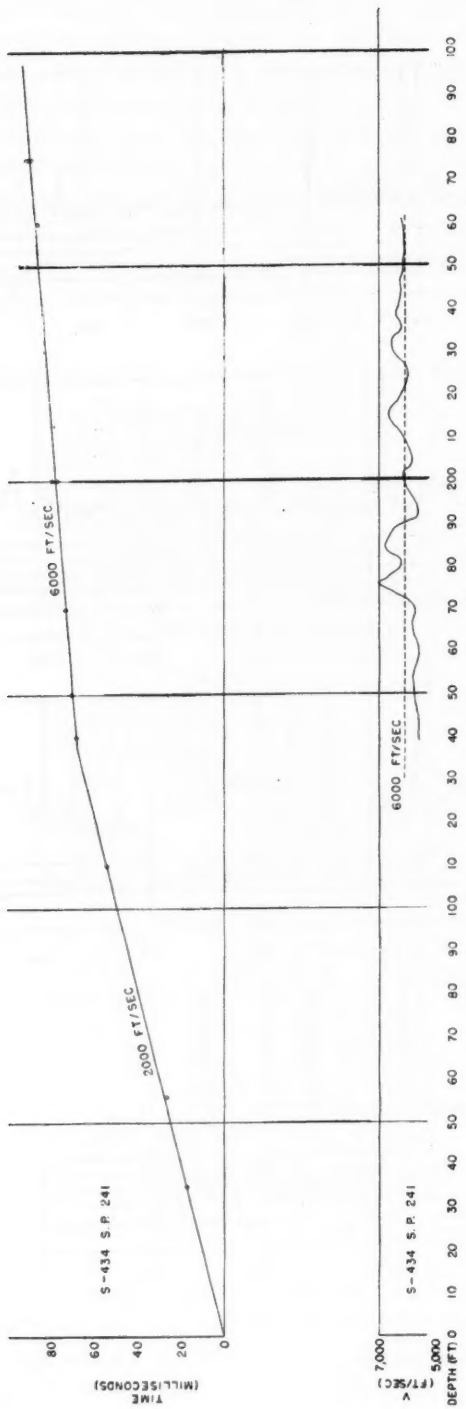


FIG. 8. Seismic and velocity log data from the same hole.

2 percent, or 10 microseconds when $V = 10{,}000$ ft/sec. When the traveltimes are integrated over a 500-foot interval, the probable error is less than 0.2 percent, whereas the highest possible precision obtainable with conventional seismic well velocity surveys over such an interval is 1 percent. For high velocities, the probable error of seismic surveys may be as high as 5 percent. When the logging measurements are integrated over 10,000 feet, the probable error becomes less than 0.05 percent, as compared with approximately 0.07 percent for seismic measurements. Thus it can be said that the precision of the integrated logging measurements over long intervals is such that the chance of the logging value being in error more than 0.25 percent is less than 1 in 1,000. The chance of seismic and integrated logging values differing by more than 5 milleseconds is likewise about 1 in 1,000 (assuming no instrumental or systematic errors occur in either measurements). It should be noted that the chance for the latter kind of errors in conventional seismic velocity surveys is by no means negligible.

The velocity logging instruments described above appear to be primarily useful for obtaining accurate velocity surveys for use in interpreting seismic records. Besides yielding rather precise time-depth data, the velocity log also shows promise of accurately locating the depth to reflecting horizons. There exists also the possibility that a knowledge of the velocity distributions associated with various types of reservoirs will suggest new methods of interpretation of reflection data.

The velocity log appears also to offer interesting possibilities for correlation and for the identification of rock types. This is suggested, for example, by the fact that limestones are distinguished from shales, even of high velocity, by the absence of shear waves in shale formations. Thus it may be possible in some cases to identify rocks even without measuring their velocities.

Further, the relation between porosity and velocity is being studied. It can be shown that where porosity variations occur without other changes in lithology, significant velocity variations will occur which can be measured with the new method described in this article. For example, when the seismic velocity is 7,000 ft/sec, the decrease in velocity accompanying a 1-percent increase in porosity can be as great as 0.5 percent; when the velocity is 10,000 ft/sec, the corresponding decrease can be as great as 1 percent.

CONTINUOUS VELOCITY LOGGING*

G. C. SUMMERS† AND R. A. BRODING†

ABSTRACT

A method for obtaining a continuous well log of formation acoustic compressional velocity is described. The instrument is composed of an acoustic pulse generator separated from a receiver by a five-foot acoustic insulator. Means are provided for generating an acoustic pulse and automatically selecting and recording the first-break travel time as detected by the receiver. The instrument has a range of 5,000 to 25,000 feet per second and an accuracy better than 5 percent. The log is taken in a conventional well logging manner at speeds of 100 to 150 feet per minute.

Typical logs are illustrated along with their probable correlation to seismic reflection horizons and lithology in the borehole.

INTRODUCTION

Exploration seismologists have long needed more detailed control of the physical variables involved in the interpretation of their data. Despite the large number of petroleum discoveries resulting from seismic exploration, the exact nature of the horizons that produce the reflections is unknown. The questions (1) how thick does a bed providing a given velocity contrast have to be to give a reflection? (2) how important are density contrasts in seismology? (3) does the character of a reflection produced by a number of thin beds differ in any obvious way from a reflection produced by a single thick bed? and (4) is it possible to distinguish between reflections originating from interfaces where velocity increases and those originating from interfaces where velocity decreases? are all largely unanswered. This paper discloses development of a continuous velocity logging instrument which may, after more extensive use, help answer these questions and many others. The velocity range of the instrument is 5,000 to 25,000 feet per second. Logging speeds well over 100 feet per minute may be used. Nominal accuracy is plus or minus five percent. The instrument also provides a recording of the amplitude of the formation component of the received acoustic energy simultaneously with the velocity record.

BASIC CONSIDERATIONS

When initial steps were taken in the development of a continuous velocity logging instrument, the first basic scheme considered was one which utilized a source of single toned, or sinusoidal, sound and either one or two receivers spaced therefrom. This system of transducers would be suspended from a logging cable and moved in the borehole. Prior work had shown that when sound sources and receivers were hung in boreholes with no clamping to the wall, several modes

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† Magnolia Petroleum Company, Field Research Laboratories, Dallas, Texas.

of propagation were present. In this case the desired mode was the one in which the energy passed from the transmitter, through the drilling mud, and into the formation, then through the formation to a point approximately opposite the receiver, and finally bridged the drilling fluid into the receiver. This mode is much like the first refracted wave in seismology. Undesired modes travelled through the drilling fluid at the compressional velocity of the mud or lower. Velocity determination would involve measuring phase changes of the formation signal with depth though there appeared to be no way to eliminate the undesired

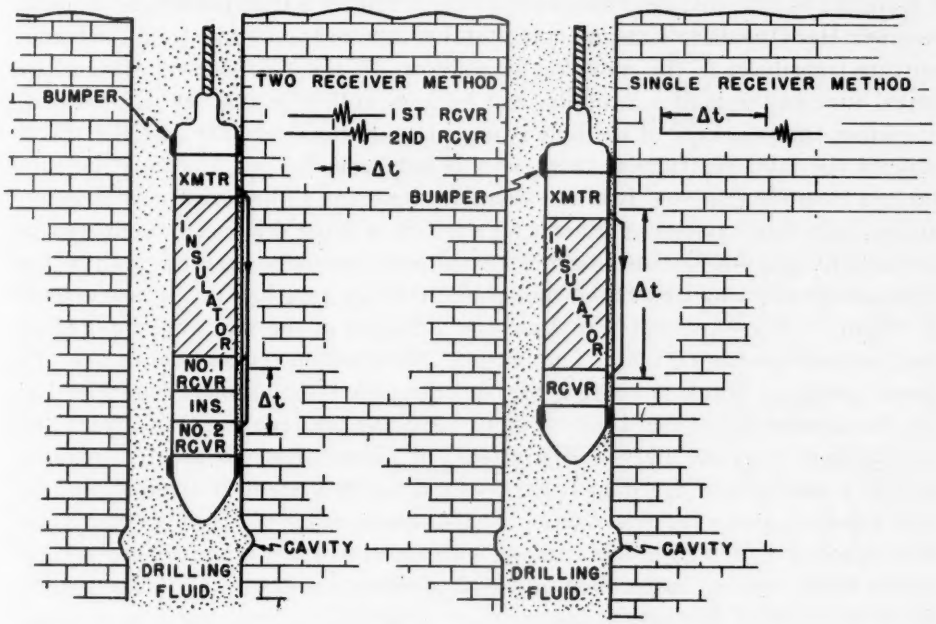


FIG. 1. Velocity logging by pulse methods.

components from the measurement. Another difficulty with continuous wave schemes is that standing waves are set up in the hole as in an organ pipe. Frequency modulation of the source might, however, have eliminated this difficulty had it been the only one. Nevertheless, continuous wave means were ruled out without a thorough evaluation though they would have permitted velocity determination at frequencies comparable to seismic frequencies.

Since the formation signal was known to be the only component which traveled at velocities higher than 5,000 feet per second, work was concentrated on pulse systems. Here a sound source of high intensity ultrasonic pulses is used. The formation component, travelling at highest velocity, arrives at a receiver first, and since the measuring system picks only the first break, the other signal components cause no interference.

Alternate means for velocity logging by pulse methods are shown in Figure 1.

The first of these utilizes a transmitter of acoustic impulses located remotely from two receivers. The nearer receiver receives the signal from the formation first, a time Δt ahead of the second receiver. Measurement of Δt, with due consideration to the receiver spacing, determines formation compressional velocity. The transmitter and the receivers are isolated from each other by acoustic insulators which either attenuate any signal transmitted down the instrument directly or delay such signal enough that it arrives later than the formation signal. Rubber, for example, both delays and attenuates. The system to the right of Figure 1 is similar to that just described except that it utilizes a transmitter and a single receiver. Here the delay time, Δt, is the total minimum travel time from the transmitting transducer to the receiving transducer. In the two receiver system the travel time in the mud is cancelled out because both receivers see it, provided, of course, that the bore of the hole is true. In the single receiver case the travel time in the mud, instrument cases, etc., is not cancelled out and must be subtracted from the final log. It is an essentially constant and relatively small error, again neglecting cavities or other irregularities of large dimension compared to instrument spacing, because logging instruments normally drag the wall of the hole and do not hang free. Small rubber bumpers are attached to the instruments in Figure 1. These prevent actual metallic scraping of the wall and thus reduce mechanically generated noise. The present limitation on the amount of acoustic power usable in borehole instruments and the high attenuations encountered at the frequencies used permit only a limited spacing between the transmitter and the farthest receiver. Larger separations, of course, lead to greater inherent accuracy and greater freedom from cavity error. A system of large separation will, however, give a log of less detail. At the present stage of development acceptable signal-to-noise figures are attained with about five feet of measuring interval in the single receiver instrument and with somewhat less spacing in the two receiver instrument. Because of the accuracy required in comparing data obtained from these logs with velocity data obtained by conventional seismic well shooting and because of the much greater simplicity of borehole equipment, most work at Magnolia has to date involved use of a single receiver system as shown at the right of Figure 1.

Since the frequencies involved in pulse measurements are in the ultrasonic range, a comment on dispersion is in order. The only statement that can be made at this time is that dispersion errors are evidently less than the five percent accuracy claimed for the instrument. The calibration scheme (a comparison with seismic well shooting data) probably reduces dispersion error to a still smaller percentage.

INSTRUMENTATION OF SINGLE RECEIVER PULSE SYSTEM

Figure 2 is a simplified block diagram of the single receiver pulse system being used. Borehole instrument power is supplied from the surface. Provision is made for the simultaneous recording of the amplitude of the formation signal.

Twenty to thirty times per second high intensity ultrasonic pulses are sent into the formation by the transmitter and simultaneously a time break, or synchronization pulse, is dispatched up the cable. The composite received signal is amplified and also sent to the surface, in some cases over the same leads as the sync pulse and the power. The sync signal, arriving first at the surface, triggers a gate of two milliseconds duration which in turn accomplishes two things;

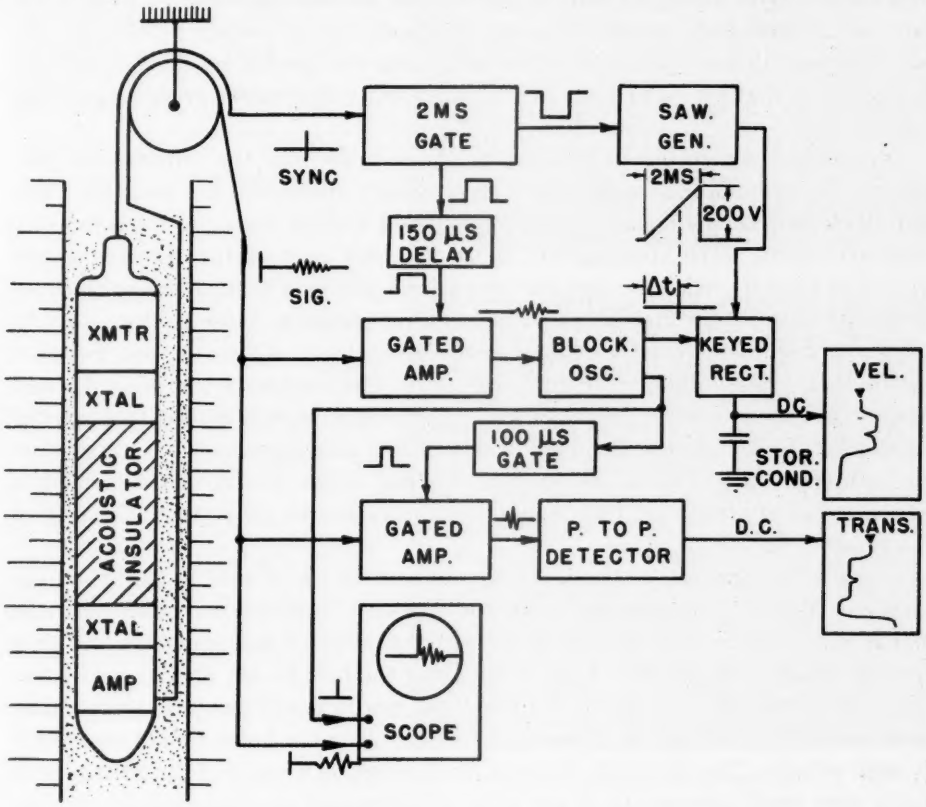


FIG. 2. Block diagram of combined velocity—transmission acoustic logging system.

first, it turns on a sawtooth generator which generates a voltage proportional to time and rising from zero at the rate of 100 volts per millisecond; secondly, the gate is passed through a delay device and then opens the gated amplifier of the velocity logging signal channel after the sync pulse is over but before the first break of the received signal arrives even for the highest velocity formations. The output of the gated amplifier, composed of the received signal and minus the sync signal cross-feed, triggers a blocking oscillator with its very first break from the base line. Thus the output of the blocking oscillator is a pulse delayed the time Δt from the sync pulse, this time being equal to the transit time in the

formation plus the known error time. The pulse is used to key a rectifier which stores on a condenser whatever voltage appears at that instant on the linearly increasing sawtooth. For example, if Δt is one millisecond, 100 volts will be stored on the storage condenser and held at least until the next cycle of events about one-twentieth of a second later. If the instrument moves into a higher velocity formation, less voltage is stored on the condenser because the blocking oscillator fires earlier. With a logging rate of 150 feet per minute, each five foot section is sampled at least forty times. The varying direct current voltage across the condenser is recorded in such a way that increasing voltage drives the recorder pen to the left so that the logs have a non-linear velocity calibration increasing to the right.

Let us now return to the blocking oscillator to see how the transmission amplitude logging channel works. We have already discussed the multiple path nature of the received signal and have concluded, that in regard to the composite received signal, when spacings are short the only part of the received signal known to have travelled through the formation is the very first part. The blocking oscillator fires at the first break. The blocking oscillator pulse is thus used to trigger a 100 microsecond gate (one-tenth millisecond) which in turn switches on another gated amplifier for only that time. The output of this second gated amplifier is then made up solely of energy known to have travelled through the formation. This energy is detected and recorded simultaneously as a transmission amplitude log. This is not a log of the true transmissivity of the formation in the frequency band used since the transducers are not clamped to the wall of the hole.

Finally, in regard to instrumentation, an oscilloscope is used to view the total received signal. A small signal from the blocking oscillator is mixed with the signal appearing on the oscilloscope so that the operator may check at any time how accurately the tracking pulse is following the first break. Should the instrument pass through a bridge in the borehole, mechanically generated noise may produce faulty tracking which would in turn result in the indication of erroneously high velocity. The fact that the receiver channel, as a result of the gating, is on for a very small proportion of the total time reduces the probabilities of noise triggering, but it is still advisable to have some way of knowing if it does occur, and also some way of knowing at what level to set the gain control.

Figure 3 shows two typical oscillograms recorded at the surface. The upper signal was received while logging the Austin Chalk formation in a laboratory test well. Delay from the start of the trace to the first break is approximately 0.6 milliseconds which, with the five foot spacing, represents a velocity of 9,000 feet per second. This velocity is high enough that the separation of the received signal into its three major components is apparent. The formation component, having a frequency of about eleven kilocycles, has travelled at formation bulk velocity. The second arrival, composed of much higher frequency energy, has travelled at a velocity of 5,000 feet per second. This has been tentatively identi-

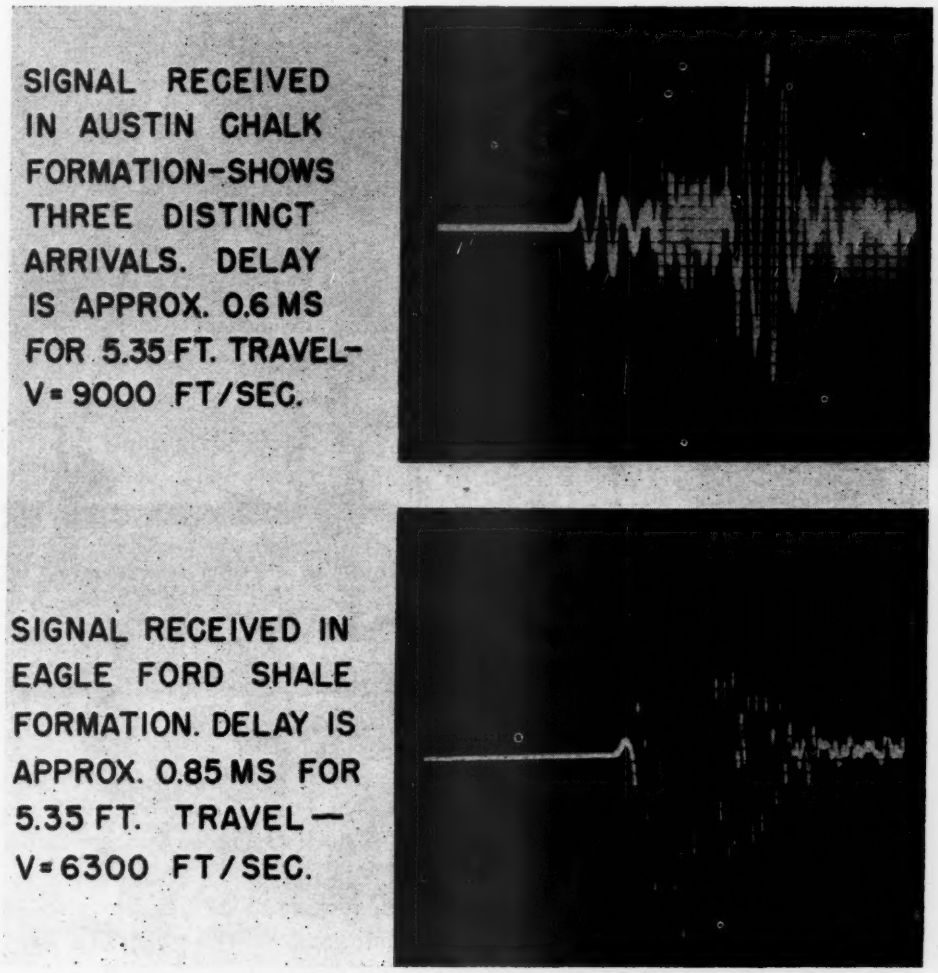

SIGNAL RECEIVED IN AUSTIN CHALK FORMATION-SHOWS THREE DISTINCT ARRIVALS. DELAY IS APPROX. 0.6 MS FOR 5.35 FT. TRAVEL- V = 9000 FT/SEC.
SIGNAL RECEIVED IN EAGLE FORD SHALE FORMATION. DELAY IS APPROX. 0.85 MS FOR 5.35 FT. TRAVEL — V = 6300 FT/SEC.

FIG. 3. Typical signals of the received pulse as recorded at the surface.

fied as the bulk compressional velocity of the drilling fluid. The third major component, again composed of lower frequency energy, has travelled at a velocity of 3,700 feet per second. This velocity is identified with the velocity of a wave discussed by Horace Lamb.* This is a modified wave travelling in a fluid of bulk modulus, k, bounded by a tube, the wall of which has a shear modulus, μ. Its velocity is as follows:

$$\text{Corrected velocity} = \text{Free fluid velocity} \times \sqrt{\frac{\mu}{\mu + k}}.$$

* "On the Velocity of Sound in a Tube as Affected by the Elasticity of the Walls," by Horace Lamb, "Manchester Memoirs," Vol. 42, No. 9 (1898).

FIG. 4. Complete subsurface logging instrument.

The lower oscillogram was taken while logging the Eagle Ford shale formation in the same laboratory test well. Here the three components of the received signal are run together and only the formation bulk velocity of 6,300 feet per second can be picked.

It should be pointed out that the automatic picking of the first break rejects these later arrivals. A great deal of latent information is thus thrown away. Future logging systems may record these components separately both with regard to transmission amplitude and velocity.

Figure 4 shows a photograph of the instrument ready to log. The black section in the center is the five foot acoustic insulator. The transmitting transducer is in the steel case just above the insulator and the receiving transducer is at the top of the steel case just beneath the insulator. The over-all instrument length is $9\frac{1}{2}$ feet and the diameter $3\frac{3}{8}$ inches. The rubber bumpers, which are removable, make the maximum outside diameter of the order of 4 inches, depending upon what size bumpers are selected.

Figure 5 shows a partly exploded view of the instrument. At the upper left is seen the high voltage pulser, or relaxation oscillator, and to the right of this is a barrel enclosing the barium titanate transmitting transducer, similar to the one on the platform below. At the upper right is the complete receiver with the small barium titanate receiving transducer at the top of this chassis. Acoustic coupling

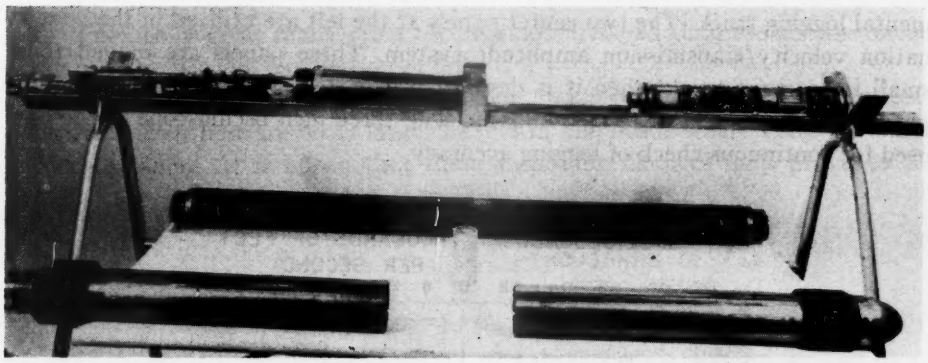


FIG. 5. Exploded view of the subsurface instrument.

for both transducers is provided by immersing them in oil. Means are provided at the bottom of the receiving chassis to attach a well geophone which replaces the instrument nose piece when velocity logs and conventional well velocity surveys are to be run together. A velocity log can be run on the trip down hole and the proper shot depths picked off the field copy.

Figure 6 is a view of the instrument compartment of the Magnolia experi-

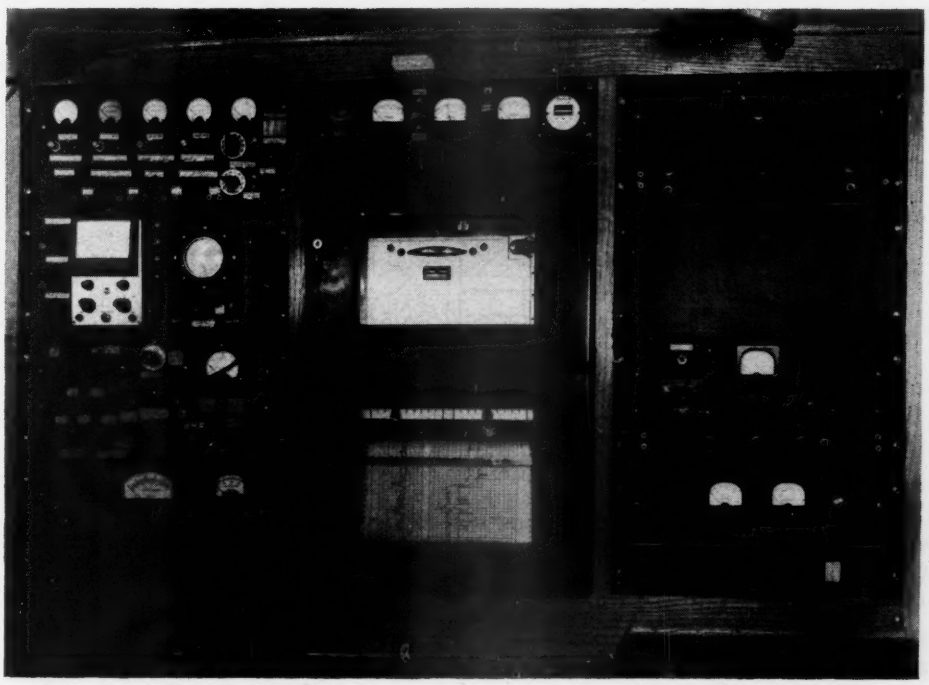


FIG. 6. Surface logging instrumentation.

mental logging truck. The two center panels at the left are utilized in the combination velocity/transmission amplitude system. These panels are moved to a small instrument truck when it is desired to operate from the cable and hoist truck of a commercial logging company. The three inch oscilloscope is the one used for continuous check of logging accuracy.

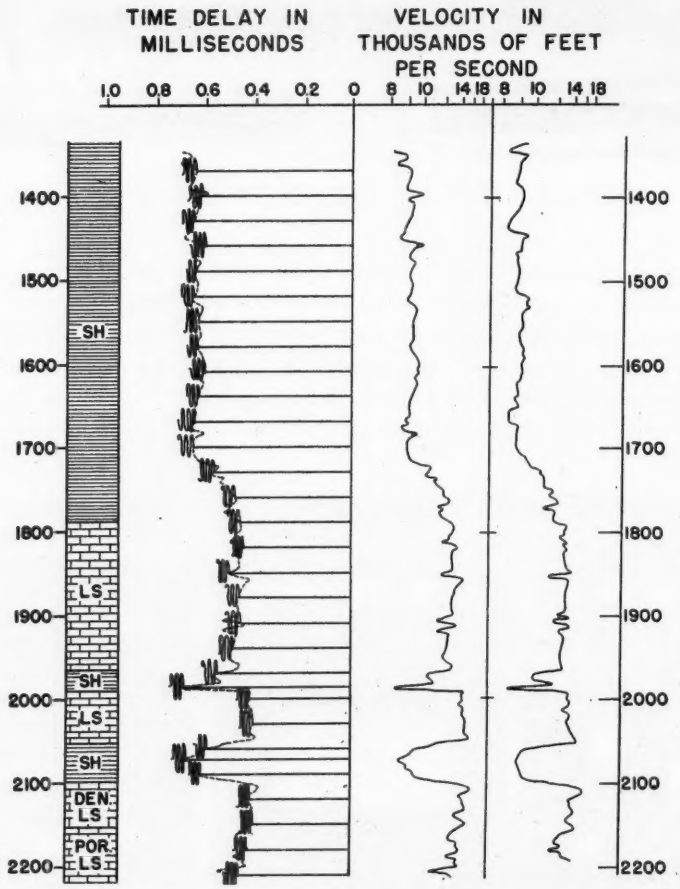


FIG. 7. Diagrammatic illustration of the variation in time delay to form a composite velocity log and the comparison of two velocity logs from different wells in the same field.

LOGS AND DATA

Figure 7 shows two velocity logs run in wells in the same field in Caldwell County, Texas. Note the transitional zone at the bottom of the large shale section. Also note the peculiar character of the thin shale layer. At the left of this figure is illustrated how one of these logs is made up from a number of received first breaks of the type already illustrated by the oscillograms of Figure 3. There

are, of course, a great many more oscillograms involved than are shown—some forty or more per five foot section of hole.

Figure 8 shows velocity and transmission amplitude logs of a laboratory test well. Note that there are often large changes in amplitude where there are small velocity changes. It is hoped that these amplitude changes may prove to be

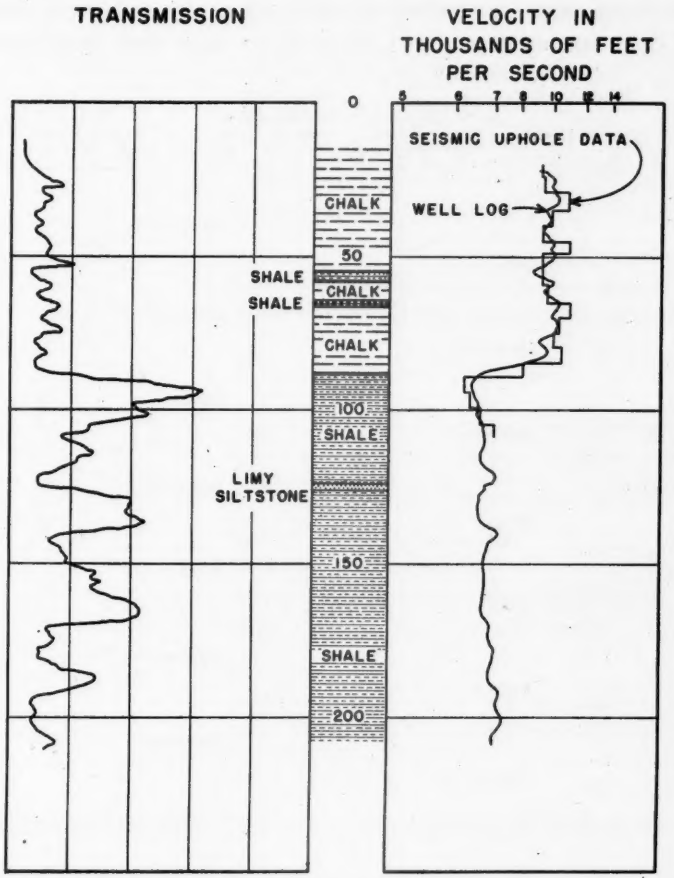


FIG. 8. Simultaneous acoustic logging of velocity and transmission amplitude in laboratory test well.

governed at least in part by density changes so that perhaps some light may be shed on the reason why occasionally seismic reflections are seen from depths which have little velocity contrast. The low transmission amplitude in the chalk section, as compared to the underlying shale, is accounted for by the severe weathering found in the Austin Chalk which lies near the surface. Superimposed on the velocity log is a broken line graph of seismic uphole data taken by Magnolia's research

seismic crew. The accuracy attainable in their measurements is of the same order as the logging accuracy. The check is good.

Figure 9 shows sections from velocity and commercial resistivity logs of three wells; the first in Hopkins County, Texas, the second in Randall County, Texas, and the third in Rio Arriba County, New Mexico. As a rule harder rocks have higher resistivity because of lower water content, and it is thus not surprising to see such remarkable correlation. Velocity logs, like resistivity logs, may be interpreted quantitatively as well as qualitatively since both have definite scales.

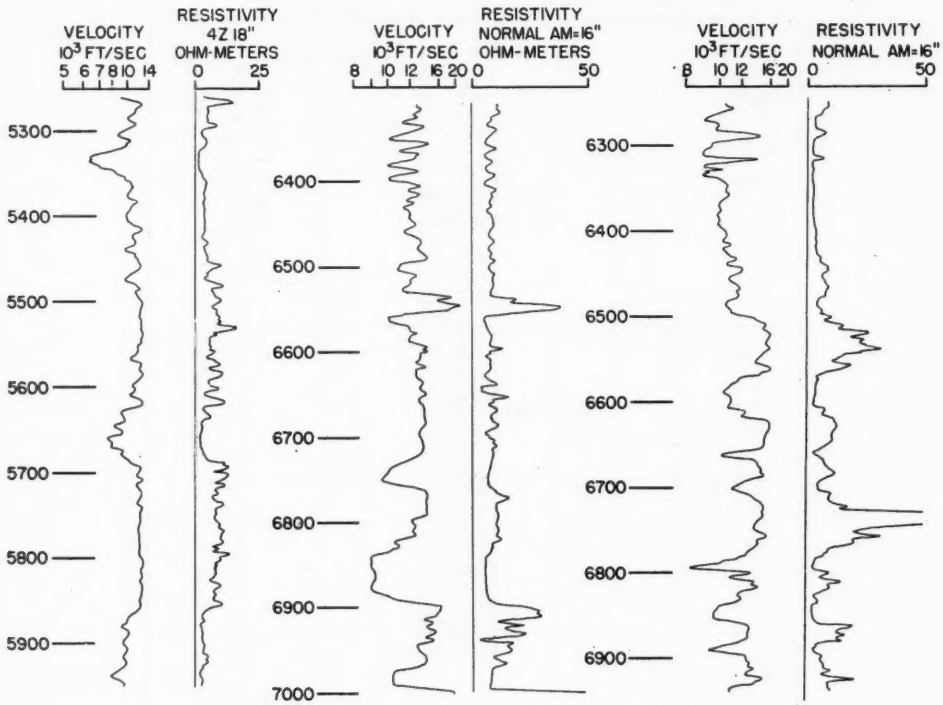


FIG. 9. Velocity-resistivity comparison in three widely separated wells.

Some parts of the velocity logs are better developed than the equivalent parts of the resistivity logs. The velocity logs have more limited dynamic range since from 5,000 to 25,000 feet per second is the total range likely to be encountered.

A series of velocity logs has been taken where conventional seismic velocity surveys were also made. Occasionally in these geophone surveys reverse first breaks are obtained which indicate that the first motion of the geophone was upward rather than downward. Figure 10 illustrates one such case. The lower seismogram, taken with the geophone at 7,500 feet, shows the first break to be upward. Moving the geophone up twenty-five feet gave a normal break. The log shows that 7,500 feet is the top of a low velocity stringer.

Interval velocities for intervals larger than five feet are found from velocity logs by integrating the desired interval with a planimeter and dividing by the thickness. A time-depth curve may be constructed from these interval velocities. Figures 11 and 12 show interval velocity and time-depth curves derived from conventional well surveys and from logs. The interval velocity data in Figure 12

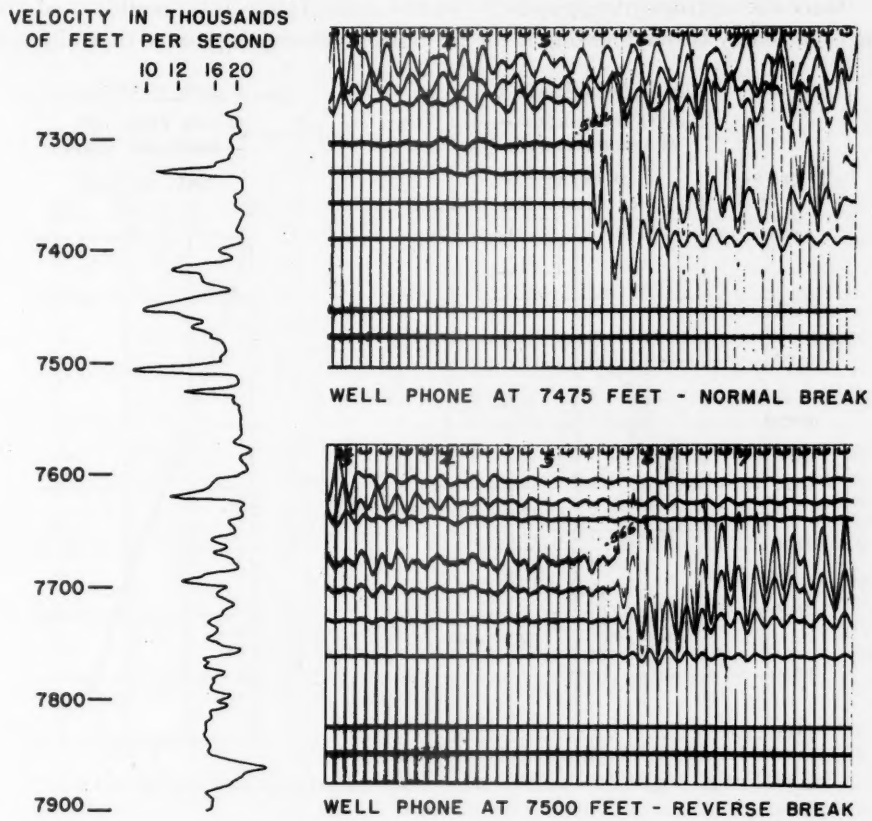


FIG. 10. Illustration of a reverse and normal geophone break and the associated velocity log.

is not so good as the claimed plus or minus five percent. The time-depth curve based on these same data, however, gives an answer only four percent high at the bottom of the hole. In general, the logs are more accurate than the conventional seismic data for intervals shorter than 300 feet, but the seismic data is not questioned on the longer intervals.

Figures 13 and 14 are comparisons of velocity logs of the same wells studied in Figures 11 and 12 respectively and seismic reflection records straddling these two wells. After five expert interpreters had picked five different times for the onsets of the more apparent reflections, an average of their picks was taken and, by use of the time-depth curves shown in Figures 11 and 12, an attempt was made

to explain the reflections by character on the velocity logs. In Figure 13 the casing bottom was at 4,442 feet. Normally the velocity log draws a straight line at approximately 18,000 feet per second in casing, but here comparison with resistivity logs taken before casing was set indicated some correlation with lithology above casing bottom.

Since the instrument responds to the first arrival time, it is possible to obtain a log of lithology through casing if the formation velocity is greater than the veloc-

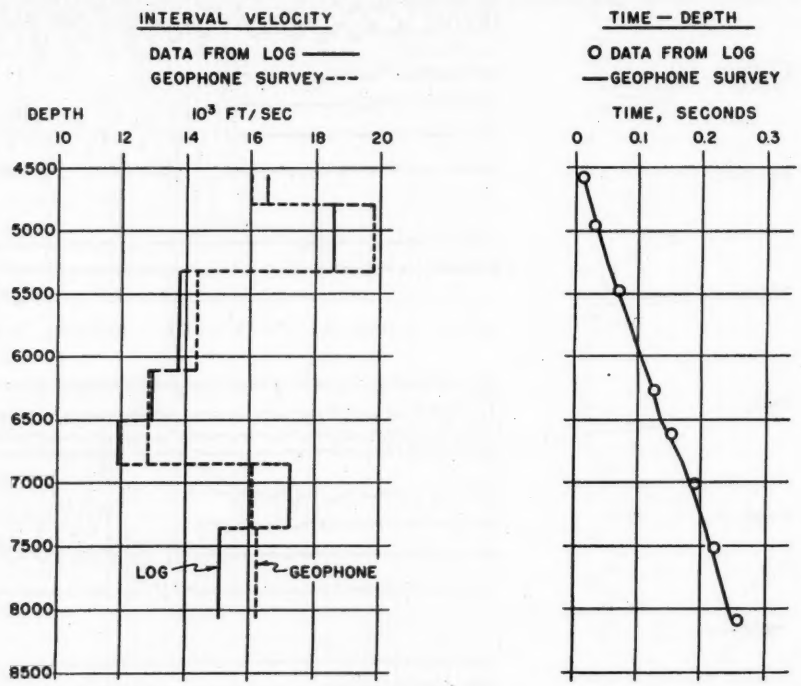


FIG. 11. Comparison of an integrated velocity log and a conventional seismic well survey, case I.

ity in the steel casing. On the other hand, it is possible to obtain a velocity lower than the velocity of casing under conditions where the amplitude of the casing signal is very weak compared to the formation signal. Under such conditions it is not possible for the weak casing signal to trigger the timing circuit and triggering then occurs on the larger but later formation pulse. It is certain, however, that such a log is not accurate because of the possibility that triggering may take place from either signal. At about 4,530 feet there is a sudden increase in velocity which correlates with the 0.805 second reflection. There is no apparent velocity interface large enough to give the next reflection, but it is remotely possible that it may be tied in with a density change since the top of the Pennsylvanian was picked at 5,480 feet on the resistivity log. The 1.030 second reflection is

evidently from a number of interfaces. The 1.098 second reflection is well accounted for by the log and the 1.180 second reflection checks fairly well. The reflection from the granite at 1.270 second is probably from a combined velocity-density change since the velocity change is small.

In Figure 14 the log goes nearer the surface than reflections can be picked.

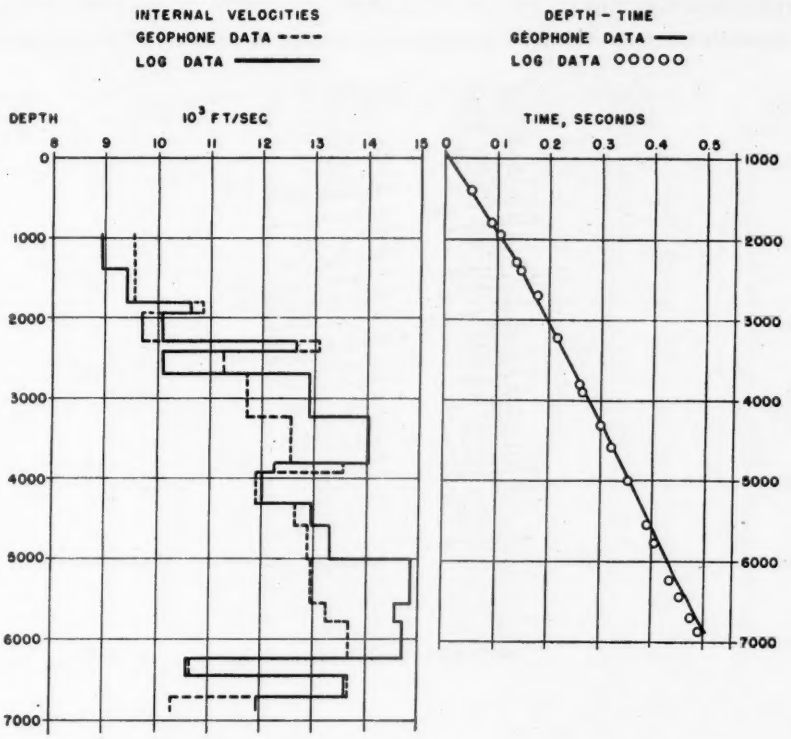


FIG. 12. Comparison of an integrated velocity log and a conventional seismic well survey, Case II.

It is hard to see why there is a reflection at 0.452 second and not at 2,280 feet on the log where a definite interface was shown in both velocity and resistivity logs. The reflection pick may simply be off this much. The 0.592 second reflection may be from the interface at 2,700 feet. The reflection at 0.760 second is doubtless from the low velocity stringers starting at 3,870 feet. The 0.860 second reflection is well defined whereas that at 1.055 is questionable. Reflections at 1.122, 1.190, and 1.228 second are explained by the log.

CONCLUSIONS

The following conclusions may be drawn from this work.

1. Velocity logs have been obtained which check seismic up-hole data within five percent.

2. The velocity log appears to be a powerful tool to the seismologist in determining reflection horizons and in making an analysis of his surface oscillograms.

3. Reflection horizons are not always obvious from a velocity log. Suggested explanations are:

a. Multiple seismic reflections from a single horizon may indicate fictitious reflection horizons.

b. Possible contrast in density without a change in velocity. The transmission

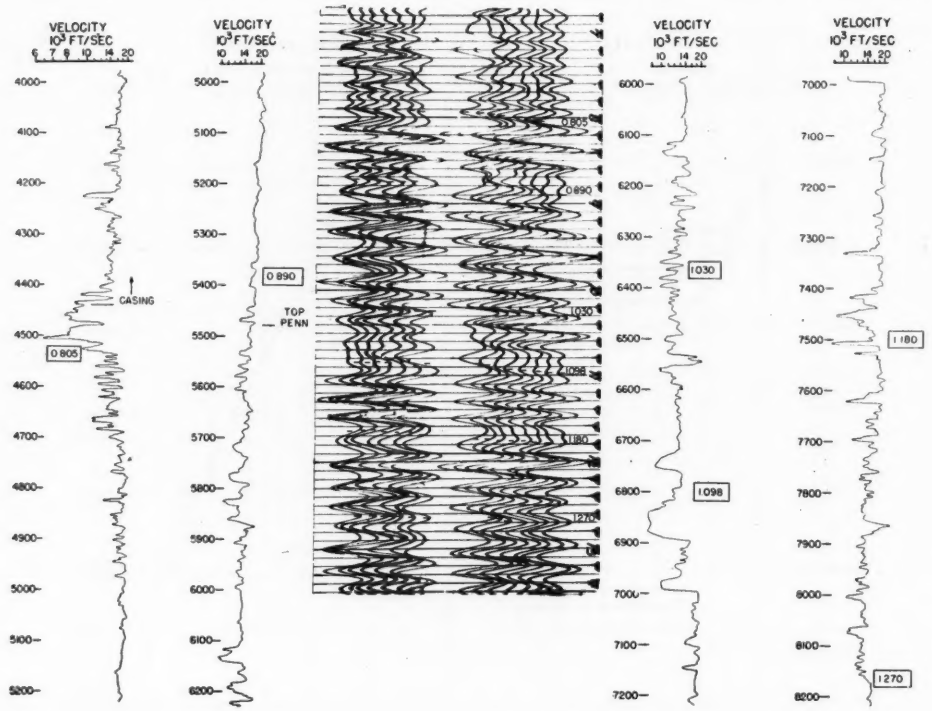


FIG. 13. Velocity log versus reflection record, case I.

amplitude log should be an aid when these situations are encountered.

4. Velocity logs reflect lithology and are often very similar to resistivity logs.

5. Reflection horizons versus velocity contrasts can be correlated from well to well in a given area. A scale can be set up to give a qualitative prediction of reflections—reflections can be graded by bed thickness and by velocity contrast where density is relatively constant.

6. Use of this tool has been preliminary. Its full utility will be realized when more field data have been compiled. It will not replace the conventional geophone surveys, for this technique does an excellent job of obtaining an accurate transit time to a particular depth. It may well be that future improvements and larger

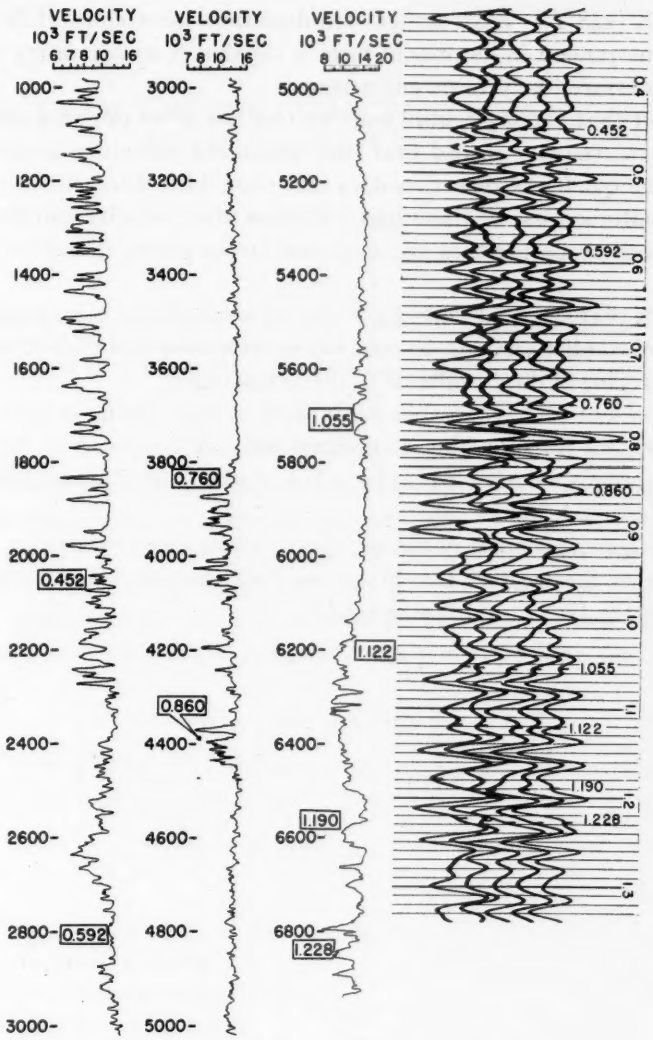


FIG. 14. Velocity log versus reflection record, case II.

measuring intervals may improve the accuracy to the extent that planimetering a velocity log to a given depth may give a surprisingly accurate figure for travel time to that depth. The present instrument does not work through casing and thus, when a well which is to be shot with a conventional survey is being followed, a log is run just before each string of casing is set. When a log is being run in a cased hole, the first arrival is usually through the casing at the plate velocity of sound in steel.

7. Use of the barium titanate transducers imposes a serious limitation on the instrument in regard to maximum operating temperature, this being approxi-

mately 120°C. (248°F.). Final design will doubtless incorporate different transducers. The instrument in its present form is capable of withstanding the highest hydrostatic pressure likely to be encountered.

8. It is felt that the main utility of the tool lies in its presentation of a continuous interval velocity record that may point out reflection horizons as well as evaluate the quality of reflection data that should be obtained. It is also quite likely that continued use of these logs will show that velocity can be related to many other rock properties that are of interest to the geologist and to the petroleum engineer.

9. It is felt that since the running of the log would be no more expensive than the running of a resistivity log, its use will be extensive and thus it will increase greatly the backlog of data available to the seismologist.

10. The present tool is operable over cables of well logging service companies and has provisions for attaching a conventional well geophone to its nose. This allows a continuous velocity log to be taken during a routine geophone survey with little additional time or expense.

Acknowledgment is made of the invaluable assistance rendered by the following members of the staff of the Magnolia Field Research Laboratories: Allen Stripling, Warren Hicks, and Wallace Allen.

A NOMOGRAM FOR THE COMPUTATION OF TIDAL DEVIATIONS OF THE VERTICAL*

A. B. MALONE†

ABSTRACT

It is possible to adapt a nomogram, devised by Thomas A. Elkins[1] for the computation of tidal variations in the vertical component of the earth's gravitational field, to the computation of tidal deviations of the vertical. The nomogram is explained and illustrated and a worked example given.

INTRODUCTION

Gravity and horizontal pendulum measurements are now widely used as a source of information on the shape and elastic constants of the earth. Calculation of the theoretical effect of the tidal forces on the vertical component of gravity is reduced to a simple routine matter by the use of Elkins' nomogram. The purpose of the present paper is to show how the nomogram may be adapted to simplify the calculation of the horizontal component, or the deviation of the vertical.

TIDAL GRAVITY THEORY

The deviation of the vertical due to the gravitational attraction of a single celestial body can easily be shown to be given by[2]

$$\Delta\psi = (3\gamma MR/2g\nu^3) \sin 2\phi \qquad (1)$$

where

$\Delta\psi$ = deflection of the vertical due to tidal force.
γ = gravitational constant.
M = mass of celestial body.
R = mean radius of the earth.
ν = geocentric distance of celestial body.
ϕ = geocenteric zenith distance of celestial body at the point of observation.
g = mean value of gravity on earth's surface.

In the above equation ϕ can be derived by means of the equation

$$\cos\phi = \cos\lambda \cos\delta \cos t + \sin\lambda \sin\delta \qquad (2)$$

* Manuscript received by the Editor November 30, 1951.

† Anglo-Iranian Oil Company, Newark, Notts., England.

[1] Thomas A. Elkins, "Nomograms for Computing Tidal Gravity", *Geophysics*, Vol. VIII (April, 1943), 134–145.

[2] Heiland (Geophysical Exploration) 1946 or Doodson and Warburg (Admiralty Manual of Tides) 1941.

where

λ = latitude of observation.
δ = declination of heavenly body.
t = local hour angle of heavenly body.

In general, however, the direction of the deviation of the vertical is also required,

$$\Delta\psi_{\text{south}} = (3\gamma MR/2g\nu^3) \sin 2\phi \cos A.$$
$$\Delta\psi_{\text{west}} = (3\gamma MR/2g\nu^3) \sin 2\phi \sin A.$$

where A is the azimuth of the celestial body.

From spherical trigonometry

$$\sin A \sin \phi = \cos \delta \sin t$$

and using equation (2), we derive

$$\cos A \sin \phi = \cos \delta \sin \lambda \cos t - \sin \delta \cos \lambda$$

Hence

$$\Delta\psi_{\text{south}} = 2k \cos \phi(\cos \delta \sin \lambda \cos t - \sin \delta \cos \lambda)$$
$$\Delta\psi_{\text{west}} = 2k \cos \phi \cos \delta \sin t$$

where $k = (3\gamma MR/2g\nu^3)$

The Friauf network (Fig. 1 of Elkins, loc. cit.) is devised for the solution of the equation for the great circle distance between two points on a sphere

$$\cos c = \cos a \cos b + \sin a \sin b \cos C$$

If $a = 90 - \lambda$, $b = 90 - \delta$, and $t = C$

$$\cos c = \sin \lambda \sin \delta + \cos \lambda \cos \delta \cos t = \cos \phi.$$

Thus, the network is directly applicable to the solution of equation (2) if the upper scale marked "sum of sides" is changed to read 0 to 180° from left to right. The centre scale, if calibrated linearly, will read directly the value of $\cos \phi$.

If we now substitute $90 - \lambda$ for λ, $-\delta$ for δ, we get

$$\cos \phi' = - \cos \lambda \sin \delta + \sin \lambda \cos \delta \cos t.$$

or, if we substitute $\lambda = 0$, $90 - t$ for t, we get

$$\cos \phi'' = \cos \delta \sin t.$$

Then

$$\Delta\psi_{\text{south}} = 2k \cos\phi \cos\phi'$$

$$\Delta\psi_{\text{west}} = 2k \cos\phi \cos\phi''$$

The value of k is 0.0173 seconds of arc for the mean distance of the moon and 0.0079 for the sun. The variation in the distance of the moon is not negligible, and usually a correction is applied for the actual distance at the time of observation.

THE NOMOGRAM

We could construct three separate nomograms for the solution of the equations for ϕ, ϕ', ϕ'', but they may readily be combined on the same sheet.

For the latitude of observation λ, we mark points on the Friauf network for various values of δ from $+30°$ to $-30°$; these points will form part of an ellipse which can be used for the solution for $\cos\phi$. Using $90-\lambda$ for λ and the same values of δ we form a second ellipse, with the δ scale reversed in sign for $\cos\phi'$. A third (degenerate) ellipse is formed with $\lambda = 0$, and the local hour angle scale is altered by subtracting it from $+6$ hours for $\cos\phi''$. The nomogram for latitude 53° N. is shown in Figure 1.

Taking as an example, the calculation of the deviations due to the moon at 09.00 G.M.T. on 5th May, 1950 at Winsford, Cheshire, longitude 2°30′ W. latitude 53° N., we find from the nautical almanac, that, approximately, the moon is at 90° W. longitude, and has declination $28\frac{1}{2}°$ S. This gives the hour angle from Greenwich as $+6$ hours and from Winsford 5h. 50m. Laying a straight edge across the nomogram between 5h. 50m. on the local hour angle scale and $-28\frac{1}{2}°$ on the ellipse for $\cos\phi$, we obtain a value -0.360 on the centre scale for $\cos\phi$. Similarly using the ellipse for $\cos\phi'$ we obtain $+0.320$. For $\cos\phi''$ we use the calibration of local hour angle scale on the right hand side and the degenerate ellipse for $\cos\phi''$ and read $+0.875$ on the centre scale.

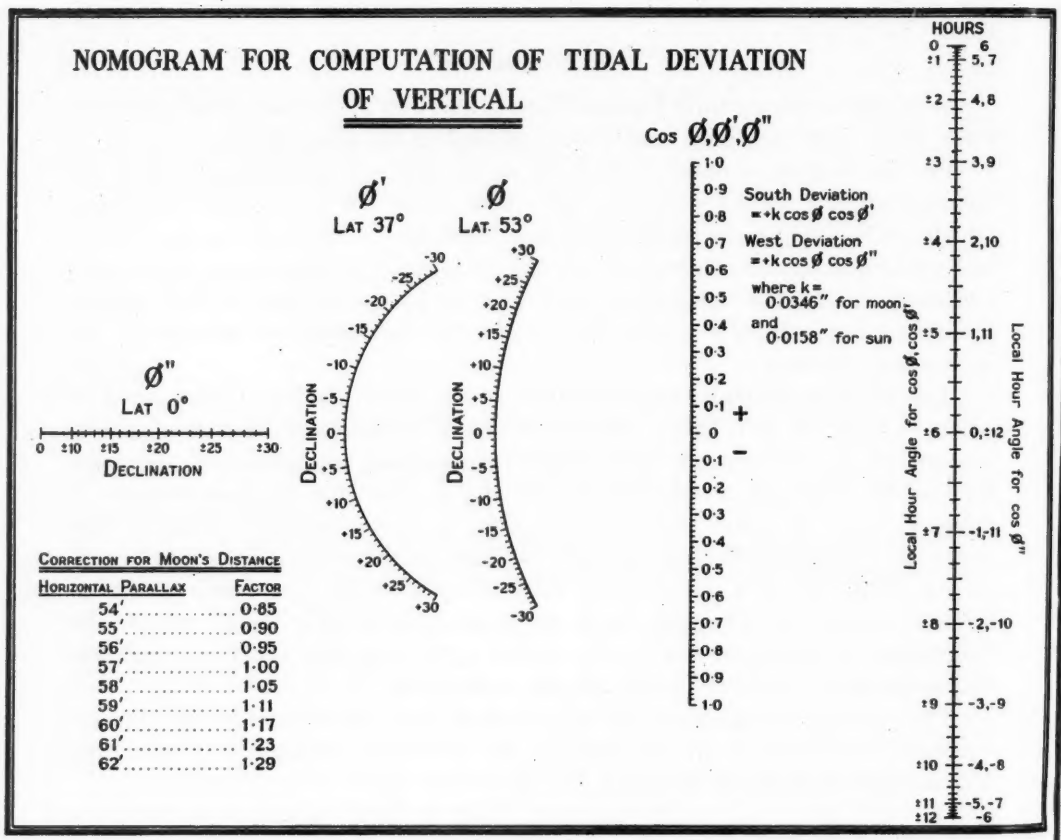
The constant for the moon is 0.0173 seconds, but this requires adjustment for the moon's distance. From the almanac the horizontal parallax is 60′ and from the nomogram the factor for 60′ is 1.17. Hence we have

$$\Delta\psi_{\text{south}} = 2k \cos\phi \cos\phi' = 2 \times 0.0173 \times 1.17 \times (-0.360) \times 0.320$$

$$= -4.66 \text{ milliseconds.}$$

$$\Delta\psi_{\text{west}} = 2k \cos\phi \cos\phi'' = -12.75 \text{ milliseconds.}$$

We have checked the nomogram against computed values of the deviation and found it to give values correct to one or two tenths of a millisecond of arc (the length of the local hour angle scale in the original was 70 cms). From the derivation of ϕ', and ϕ'' it follows that $\cos^2\phi + \cos^2\phi' + \cos^2\phi'' = 1$, and this may be useful as a check on the working.


NOMOGRAM FOR COMPUTATION OF TIDAL DEVIATION OF VERTICAL
Ø" LAT 0°
0 ±10 ±15 ±20 ±25 ±30
DECLINATION
Ø' LAT 37°
Ø LAT 53°
DECLINATION
DECLINATION
Cos Ø,Ø',Ø"
South Deviation = +k cos Ø cos Ø'
West Deviation = +k cos Ø cos Ø"
where k = 0·0346" for moon and 0·0158" for sun
HOURS
Local Hour Angle for cos Ø, cos Ø'
Local Hour Angle for cos Ø"

CORRECTION FOR MOON'S DISTANCE	
HORIZONTAL PARALLAX	FACTOR
54′	0·85
55′	0·90
56′	0·95
57′	1·00
58′	1·05
59′	1·11
60′	1·17
61′	1·23
62′	1·29

FIG. 1

The deviation is usually calculated from the equations

$$\Delta\psi_{\text{south}} = k[\tfrac{1}{2}\sin 2\lambda(1 - 3\sin^2\delta) - \cos 2\lambda \sin 2\delta \cos t + \tfrac{1}{2}\sin 2\lambda \cos^2\delta \cos 2t]$$

$$\& \ \Delta\psi_{\text{west}} = k[\sin\lambda \sin 2\delta \sin t + \cos\lambda \cos^2\delta \sin 2t]$$

and it will readily be seen that the use of the nomogram introduces a very considerable reduction in labour.

ACKNOWLEDGMENT

The writer wishes to thank the Chairman of the Anglo-Iranain Oil Co., Ltd., for permission to publish this paper.

NOMOGRAMS

Wavelength chart. This nomogram performs a simple multiplication to obtain wavelength when velocity and period are known. The period scale includes frequencies from 5 to 100 cycles per second. The velocity scale may be extended upwards to any desired value if its linear scale is maintained. The wavelength scale, in the same manner, may be extended downwards to greater values.

To lay off the period scale, which is nonlinear, the following equation may be used:

$$D = \frac{L}{RT + 1}$$

where:

- L is the length of a line measured from zero on the velocity scale to zero on the wavelength scale.
- R is the ratio of velocity to wavelength over equal scale distances. It equals 1,000/20 in this nomogram.
- T is the particular value of period to be plotted.
- D is the distance along the period scale, measured from zero on the velocity scale, to the location of the particular value of period involved.

Frequency, the reciprocal of period, may be read on this nomogram when period is known. Simply align the number (100) on the wavelength scale with the given value of period. The value read off the velocity scale divided by 100 will be frequency.

Example:

Velocity equals 5,000 ft./sec.

Period equals .040 second.

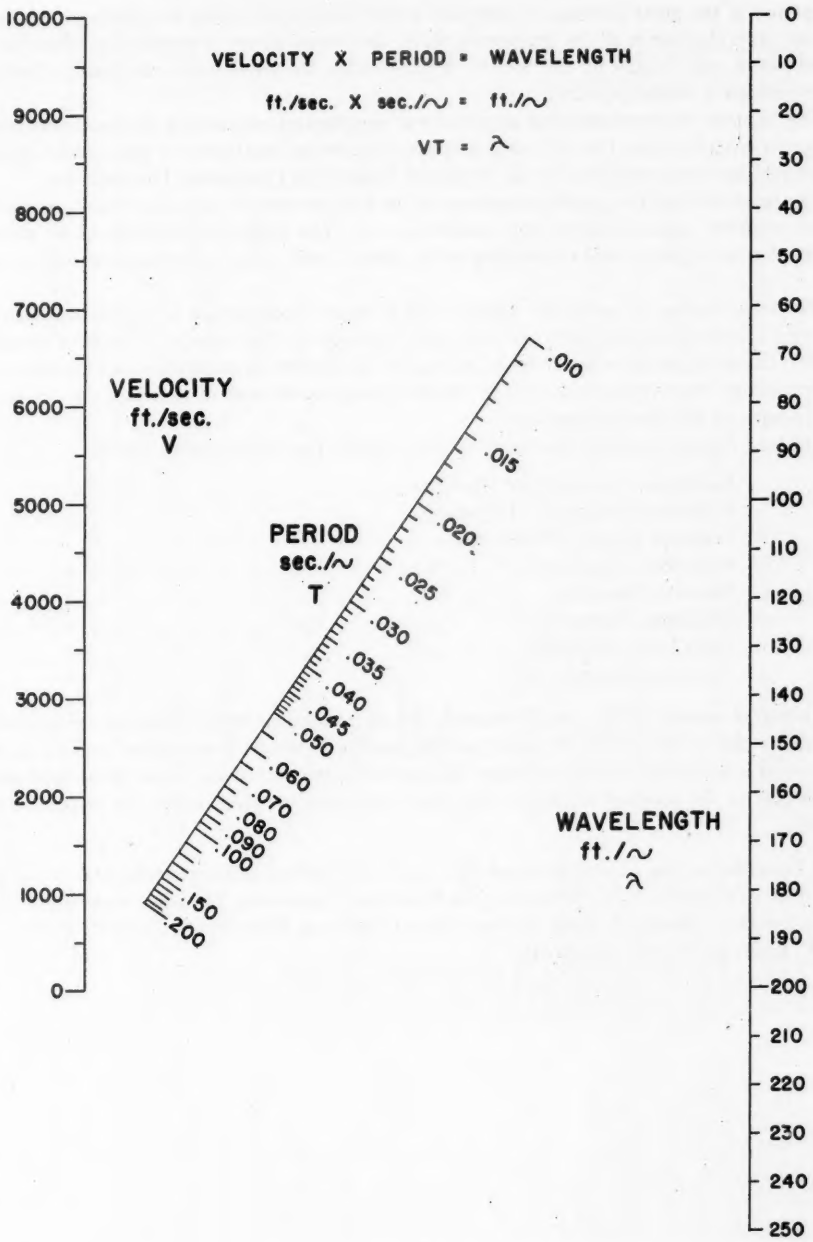
Alignment of V and T gives a wavelength of 200 feet.

Alignment of (100) and T solves for frequency, which is 2,500/100 or 25 cycles per second.

JAMES R. GAEBE
Continental Oil Company

WAVELENGTH CHART

INSTRUCTIONS: ALLIGN V AND T, READ λ



UNIVERSITY OF MICHIGAN LIBRARIES

ANNUAL SURVEY OF GEOPHYSICAL EDUCATION 1951–1952*

In view of the great shortage of personnel trained in applied geophysics which is so keenly felt this year, as is the case in all the engineering fields, the annual survey of geophysical education in the United States and Canada by the Society of Exploration Geophysicists is particularly timely. The results indicate a steady growth.

The number of departments of geophysics or geophysical engineering has increased from two in 1930 to seven in 1952. The field of geophysical engineering has found its place and a curriculum in that field has been accredited by the Engineers' Council for Professional Development.

The total enrolment in geophysics courses in the first semester of 1951–1952 was 1,083 and in the second semester, as far as figures were available, 1,161. The number of students whose major field was geophysics or geophysical engineering in the present year is 290 undergraduates and 190 graduates.

The total number of bachelors' degrees with a major in geophysics or geophysical engineering that were conferred between July 1950 and June 1951 was 97. The number of masters' degrees conferred in the same period of time was 30. A total of 330 courses in geophysics, not including courses in Meteorology, were reported as actually taught during the summer of 1951 and the two semesters of 1951–1952 by 108 faculty members.

Doctors' degrees in geophysics conferred July 1950 to June 1951 were as follows:

California, University of (Berkeley)	1
California Institute of Technology	1
Colorado School of Mines	1
Columbia University	2
Harvard University	1
Michigan, University of	1
Saint Louis University	1
Toronto, University of	7

Details of administration and of courses in the 59 institutions which returned the questionnaire are summarized in the tables. In each case the number of semester or quarter courses on the elementary (E), advanced (A) and graduate (G) levels devoted exclusively to the given field and actually taught in the summer of 1951 or the year 1951–1952 are given under the respective column headings.

* Presented at the Annual Business Meeting of the Society at Los Angeles March 24, 1952 by Rev. J. B. Macelwane, S.J., chairman of the Education Committee. The other members of the committee are D. C. Skeels, M. King Hubbert, Beno Gutenberg, Perry Byerly, John C. Hollister, Sherwin F. Kelly, and H. W. Straley III.

TABLE I

Institution	Administration		Students in Applied Geophysics				Titles of Geophysical Degrees	Degrees Conferred July 1950–June 1951			Faculty Teaching Courses in Geophysics
	Departments	Schools or Colleges	Total in Courses 1951–1952		Majors			Bachelors	Masters	Doctors	
			I	II	Undergraduate	Graduate					
Alaska, U. of	Geophysics	—	2	3	1	2	B.S., M.S.[1]	—	—	—	4[2]
Brown U.	Oceanography	—	6	1	—	—	—	—	—	—	1
Calif. U. of (Berkeley)	Geological Sciences	Letters & Science	22	23	6	3	A.B., M.A., Ph.D.	—	—	1	2
Calif. U. of (Los Angeles)	Geology, Physics	Letters & Science	—	—	—	—	B.S.[3]	3	—	—	5
Calif. Inst. of Tech.	Division of Geological Sciencies	—	12	12	4	9	M.S., Geophysical Engineer, Ph.D.	—	4	1	5[4]
Cincinnati, U. of	Geology	Liberal Arts, Graduate	12	—	—	—	—	—	—	—	1
Colorado Sch. of Mines	Geophysics	—	165	250	109	20	Geophysical Engineer, M.S.,[5] D.Sc.[6]	25	1	1	4
Colorado, U. of	Geology	Arts & Sciences	—	30	—	—	—	—	—	—	1
Columbia U.	Geology	Graduate Faculty of Pure Science	17	17	—	24	M.S., Ph.D.	—	1	2	3
Dalhousie U.	Physics	—	2	2	—	—	B.Sc.,[6] M.Sc.	—	1	—	1
Florida State U.	Oceanographic Institute, Geology	Arts & Sciences	—	8	—	—	—	—	—	—	(?)
Franklin & Marshall Col.	Geology	—	—	—	—	—	—	—	—	—	1
Georgia Inst. of Tech.	Geology	Ceramic Engineering	3	10	—	—	—	—	—	—	6
Harvard U.	Geology	Arts & Sciences	30	40	—	8	M.S., Ph.D.	—	3	1	2
Houston, U. of	Geology, Physics	Arts & Sciences	41	6	1 or 2	—	—[7]	—	—	—	2
Idaho, U. of	Mining	School of Mines	—	22	—	—	—	—	—	—	1
Illinois, U. of	Geology & Mining Engineering[8]	Arts	5	—	—	—	—	—	—	—	1
Iowa State Col.	Physics	—	2	2	—	2	B.S., M.S., Ph.D.[9]	—	—	—	1
Johns Hopkins U.	Geology[10]	—	—	10	—	—	—	—	—	—	1
Kansas State Col.	Physics	Arts & Sciences	10	5	5	—	B.S.	1	—	—	1
Kansas, U. of	Geology	—	20	—	—	—	—	—	—	—	1
Laval U.	Mining & Metallurgy	—	(?)		—	—	—	—	—	—	1
Lehigh U.	Mining Engineering	Engineering	8	8	6	1	B.S.[11]	3	—	—	1
Mass. Inst. of Tech.	Geology	—	33	31	22	10	B.S.,[12] M.S.,[12] Ph.D.[13]	5	—	—	3
Miami U. (Ohio)	Geology	Arts & Sciences	—	5	—	—	—	—	—	—	1
Michigan Col. of M. & T.	Physics	—	4	4	—	4	M.S.	—	2	—	2
Michigan, U. of	Geology	Literature, Science & Arts	37	8	2	5	M.S., Ph.D.	—	6	1	1
Minnesota, U. of	Geophysics	School of Mines	17	13	1	2	Bachelor of Geophysics,[14] M.S., Ph.D.	—	—	—	1
Mississippi State Col.	Physics	Science	20	—	—	—	—	—	—	—	1
Montana Sch. of Mines	Physics	—	—	4	—	—	—	—	—	—	1
Montreal, U. of	—	—	—	—	—	—	—	—	—	—	1
New Mexico Inst. of M.T.	Physics & Geophysics	—	9	9	7	6	B.S., M.S.	4	1	—	1
New York U.	Geology	Graduate Schools[15]	24	36	—	—	—	—	—	—	7
North Carolina, U. of	Geology & Geography	Arts & Sciences	—	2	1	—	—	—	—	—	1
North Dakota, U. of	Geology	Engineering	—	—	—	—	—	—	—	—	—
Northwestern U.	Geology, Civil Engineering	Liberal Arts, Technological Institute	11	9	—	—	—	—	—	—	(?)

UNIVERSITY OF MICHIGAN LIBRARIES

TABLE I—*Continued*

Institution	Administration		Students in Applied Geophysics				Titles of Geophysical Degrees	Degrees Conferred July 1950–June 1951			Faculty Teaching Courses in Geophysics
	Departments	Schools or Colleges	Total in Courses 1951–1952		Majors			Bachelors	Masters	Doctors	
			I	II	Undergraduate	Graduate					
Ohio State U.	Geology	Arts & Sciences	—	(?)	—	—	—	—	—	—	1
Oklahoma, U. of	Geology	Arts & Sicences	60	60	—	—	—	—	—	—	1(?)
Oregon State Col.	Geology	Science	—	1	—	—	—	—	—	—	2
Pennsylvania State Col.	Division of Geophysics & Geochemistry	Mineral Industries	44	66	18	10	B.S., M.S., Engineer of Mines, Ph.D.	4	2	—	4
Pittsburgh, U. of	Geology	Arts & Sciences	30	—	2	1	—	—	—	—	1
Purdue U.	Physics	—	—	15	—	—	—	—	—	—	1
Redlands, U. of	Geology	—	16	17	4	—	B.S.[16]	8	—	—	1
Rensselaer Poly. Tech.	Fuel Resources	—	12	6	3	2	B.S.,[17] M.S.,[17] Ph.D.	—	—	—	2
Saint Louis U.	Geophysics & Geophysical Engineering	Institute of Technology, Graduate	117	151	52	23	B.S.,[18] M.S., Ph.D.	19	—	1	10
Southern Calif., U. of	Geology	Engineering	11	15	—	—	—	—	—	—	3
Southern Methodist U.	Geology	—	—	6	—	—	—[19]	—	—	—	1
Texas, A. & M. College of	Geology, Oceanog.	Engineering	20	10	5	20	—[20]	—	—	—	1
Texas Christian U.	Physics	—	14	—	—	—	—	—	—	—	1
Texas, U. of	Geology	Arts & Sciences	40	—	—	—	—	1	—	—	(?)
Toronto, U. of	Physics	Faculty of Arts	42	39	6	16	B.A.,[21] B.A.Sc.,[22] M.A., Ph.D.	6	6	7	3[22]
Tulane U.	Geology	—	12	12	—	—	—	—	—	—	1
Tulsa, U. of	Physics	Engineering & Arts	20	25	15	1	B.S.,[24] A.B.[25]	8	—	—	1
Utah, U. of	Geophysics	Mines & Mineral Industries	11	11	8	3	B.S., M.S.	6	—	—	1[26]
Xavier U.	Physics	Arts & Sciences	—	—	—	—	—	—	—	—	1
Western Ontario, U. of	Physics, Geology	—	6	6	—	1	—	—	—	—	1
West Virginia, U.	—	School of Mines	16	—	—	—	—[27]	—	—	—	1
Williams Col.	Geology	—	—	11	—	—	—	—	—	—	1
Wisconsin, U. of	Geology	Letters & Science	100	140	11	17	M.S., Ph.D.[28]	4	3	—	3

[1] With Major in Basic Geophysics.
[2] Part time.
[3] Research; but no M.S. or Ph.D. offered.
[4] Not including earthquake damage (2), hydrology (2), or geochemistry (2).
[5] In Geophysical Engineering.
[6] In Engineering Physics.
[7] Geophysical option of Professional B.S. is offered.
[8] Joint course.
[9] In Physics with Geophysical option.
[10] Department in process of complete reorganization.
[11] In Mining Engineering and in Engineering Physics.
[12] In Geology.
[13] In Geophysics.
[14] Five year undergraduate curriculum.
[15] Arts & Science and College of Engineering.
[16] In Geology.
[17] In Geophysics (Specified).
[18] In (a) Geophysical Engineering, (b) (Professional) Seismology, and (c) Hydrological Engineering.
[19] Apply to Geology degrees.
[20] Geology, Geophysics option.
[21] Honour course in Physics and Geology.
[22] Bachelor of Applied Seience in Engineering Physics (Geophysics option).
[23] Plus two Ph.D. Research Assistants.
[24] In Geophysical Engineering.
[25] In Geophysics.
[26] Two before July, 1951.
[27] No degree offered, rather auxiliary courses for degree of Petroleum Engineering.
[28] In Geology (Geophysics option).

TABLE II

Number of Semester or Quarter Courses Actually Taught, Summer 1951 to Spring 1952
E = Elementary course; A = Advanced undergraduate course; G = Graduate Course

Institution	Field Covered by Courses																		
	General Geophysics	Geophysical Theory	Geophysical Exploration (Several Methods)	Seismic Exploration	Gravity Exploration	Magnetic Exploration (including Airborne)	Geochemical Exploration	Electrical and Electromagnetic Exploration	Other Geophysical Exploration Methods	Earthquake Seismology	Geo-Electricity	Geomagnetism	Geodesy (Cartography)	Geodesy (Gravity)	Geophysical Electronics	Hydrology	Physical Oceanography	Volcanology	Other
Alaska, U. of	1E											2G							
Brown U.																	2A		
Calif. U. Berkeley		1A	2A	1A						1A									
		1G								3G								1G	
Calif., U. Los Angeles	2E										2E	2E	2E	2E					
	3A										2A	2A	2A	2A			10A		
	2G										2G	2G	2G	2G			10G		
Calif. Inst. of Tech.	1A		1A							1A			1A			2A			
	1G	1G			1G	1G		2G	1G	2G						2G			2G
Cincinnati, U. of	1E		1A																
Colorado, U. of			1E																
Colorado Sch. of Mines		2E	2E																
		1A		1A	1A	1A		1A	1A						1A				
		3G		1G	1G	1G		1G	1G										
Columbia U.	3G		1G							2G									1G
Cornell U.																	1E		
Dalhousie U.		2A																	
Florida State U.																	1G		
Franklin & Marshall Col.	1E																		
Georgia Inst. of Tech.	1E																		
	2G					1G										1A			
Harvard U.	1E			1E						1E									
	1A									1G									
Houston, U. of		2E	1E				1E									1E			1E
Idaho, U. of	1E																		
Illinois, U. of																			1E
Iowa State Col.																			10G(?)
Johns Hopkins U.	1E		1E															1E	
Kansas State Col.			1E																
Kansas, U. of			1E																
Laval U.			1E																
Lehigh U.	1E		1E	½A	½A	½A		½A											
Mass. Inst. of Tech.		4G	1E							1E									
Miami U. (Ohio)			1E																
Michigan Col. of M. & T.			1A	1A					1A										
		1G							1G										
Michigan, U. of	1A		2G																
Minnesota, U. of	1E		1E							1E									
			1G	1G				1G											
Mississippi State Col.			1E																
Montana Sch. of Mines	1E																		
Montreal, U. of	½E		½E																
New Mex. Inst. M. & T.	2A	2G	2G																
New York U.	2G																		
North Carolina, U. of			5E(?)			5A(?)												5E(?)	
Northwestern U.	3G															2E			
Oklahoma, U. of			2A																
Oregon State Col.	1E																		
Pennsylvania State Col.	1E		1E													2E			
	1A			1A	1A	1A		1A	1A							1A			
	2G		1G																2G
Pittsburgh, U. of	1E																		
	1A																		
Purdue U.	1A	1G	1A																
Redlands, U. of	1E		1A	1A	1A	1A		1A											
Rensselear Poly. Inst.	1E		1E																2G
Saint Louis U.	1E																		
	1A	6A	2A								6A				2A	4A			
	4G	2G		1G	3G	1G		1G			1G					1G			
Southern Calif, U. of																1A	1G	1G	
Southern Methodist U.	½E		½E																
Texas A. & M. Col. of	1A																1G		
Texas Christian U.	1E																		
Texas, University of			1E																
Toronto, U. of			1E																
	1A	1A	1A												1A				
	1G		1G																
Tulane U.	1E		1E										1E						1E
			1A																
Tulsa, U. of	2E		2E	2A	2A	1A		1A											
						1G													
Utah, U. of			3E	1A	1A	1A		1A											
Western Ontario, U. of	2G																		
West Virginia U.				1E	1E	1E				1E									
Williams Col.	1E																		
Wisconsin, U. of	1E	1G	1E													2E	1E		

PATENTS

O. F. RITZMANN*

ELECTRICAL PROSPECTING

U. S. No. 2,580,670. E. A. Gilbert. Iss. 1/1/52. App. 6/28/48. Assign. Radio Frequency Laboratories, Inc.

Metal Detector. A detector for metal objects on a conveyor belt having a coil through which the belt moves connected in the tuned plate circuit of an oscillator whose output is rectified and used to fire a gas tube which controls relays for signaling and marking the belt.

U. S. No. 2,581,349. W. M. Barret. Iss. 1/8/52. App. 10/3/45. Assign. Engineering Research Corp.

Method of Electrical Prospecting. A method of radio-wave prospecting in which the wave is propagated along the earth's surface and the tilt of the wave front observed along a traverse through the source.

U. S. No. 2,585,907. W. M. Barret. Iss. 2/19/52. App. 6/26/47. Assign. Engineering Research Corp.

Transmitting and Receiving Apparatus for Electromagnetic Prospecting. An antenna system for radio-wave prospecting having an insulated conductor placed on the surface of the ground with a condenser and inductance in series with the wire and energized by coupling to the inductance, the length of the wire being an odd multiple of quarter wave lengths of the resulting wave in the earth.

U. S. No. 2,586,667. G. Kunetz. Iss. 2/19/52. App. 2/27/46 and 5/16/46. Assign. Compagnie Generale de Geophysique.

Method for the Electrical Investigation of the Ground. An electric earth investigating system in which the field of telluric currents is simultaneously recorded at two stations between pairs of points whose lines are at right angles so that the resultant telluric field can be determined, and comparing the area swept by the resultant field vector at one station with that at the second station during the same time interval.

GEOCHEMICAL PROSPECTING

U. S. No. 2,590, 113. E. McDermott. Iss. 3/25/52. App. 3/12/47.

Geochemical Prospecting. A soil-analysis prospecting method in which soil samples are heated to 500°C. to decompose organic matter and subsequently heated to 600°C. to liberate additional CO_2 which is measured.

GRAVIMETRIC PROSPECTING

U. S. No. 2,589, 709. L. La Coste and A. Romberg. Iss. 3/18/52. App. 9/12/46.

Force Measuring Device. A gravimeter having the moving system frame vertically movable by a motor which is controlled from the position-indicating amplifier so that the frame is accelerated whenever the moving system closely approaches a stop and using an averaging amplifier to indicate the position of the moving system with respect to the frame.

U. S. No. 2,589,710. L. J. B. La Coste and A. Romberg. Iss. 3/18/52. App. 6/11/48.

Force Measuring Device. A gravimeter having the moving system frame vertically movable by a motor which is controlled from the position-indicating amplifier so as to avoid contact of the moving system with motion-limiting stops and which also has condenser plates for applying electrostatic forces to the moving system to retard its motion when approaching a stop.

* Gulf Oil Corporation, Patent Department.

U. S. No. 2,590,740. P. J. Walsh. Iss. 3/25/52. App. 2/5/45.

Gravity Meter. A gravimeter having a number of weights each hanging on a fine wire with the wires electrically connected in series and their resistance change indicated.

MAGNETIC PROSPECTING

U. S. No. 2,584,571. E. Frowe. Iss. 2/5/52. App. 2/24/48. Assign. Robert H. Ray Co.

Magnetometer. A self-oriented total-field magnetometer in which three coils are mechanically oscillated about three mutually-perpendicular axes and the emf generated by two of the coils used to control orientation and the emf from the third coil used to control field-neutralizing current in Helmholtz coils around the magnetometer.

U. S. No. 2,590,131. E. O. Schonstedt. Iss. 3/25/52. App. 6/5/46.

Anchoring and Connecting Means for Strain-Cored Electrical Cables. A strain connector for connecting the suspending cable to an airborne-magnetometer bird and having a disk to which the cable strain member is fastened with the conductor wires passing through holes in the disk.

U. S. No. 2,590,184. T. Koulomzine. Iss. 3/25/52. App. 4/29/47.

Magnetometer. A balance-type magnetometer whose moving system is immersed in a liquid to provide buoyant force so that the distance between the center of gravity and the knife edge may be made large.

RADIOACTIVITY PROSPECTING

U. S. No. 2,581,412. G. Herzog. Iss. 1/8/52. App. 7/6/48. Assign. The Texas Co.

Geophysical Exploration. A geophysical exploration or well-logging method in which the spectrum of natural neutrons emitted from the earth is determined.

SEISMIC PROSPECTING

U. S. No. 2,580,537. J. W. Flude. Iss. 1/1/52. App. 9/16/39, 3/7/42 and 6/4/47.

Enclosed Kite-Type Detector Carrier. A detector carrier for marine seismograph operations in which the detector is housed in the lower part of a cylindrical container whose upper part contains air and with an open-ended cylindrical shell connected to the container by fins to stabilize motion through the water when towing.

U. S. No. 2,580,636. A Wolf. Iss. 1/1/52. App. 3/1/45. Assign. The Texas Co.

Reflection Seismic Exploration. A seismograph detector array in which the detectors of each group are set out on a line perpendicular to the line of shooting and adjacent groups mixed so that the recorded traces represent signals received from an area larger than the wave length of surface disturbances.

U. S. No. 2,581,063. W. A. Alexander. Iss. 1/1/52. App. 3/16/50. Assign. Standard Oil Development Co.

Geophone. A geophone having an electret elastically supported near a metal plate so that vibration of the electret induces a voltage signal in the circuit connected to the plate.

U. S. No. 2,581,091. P. H. Foster. Iss. 1/1/52. App. 10/21/50. Assign. Standard Oil Development Co.

Continuous Line Seismometer. A continuous-line geophone having a central current-carrying conductor elastically suspended in an elastic sheath with pick-up coils wound longitudinally around sections of the sheath so that the coil wires are parallel to the central conductor.

UNIVERSITY OF MICHIGAN LIBRARIES

U. S. No. 2,581,994. A. C. Winterhalter. Iss. 1/8/52. App. 4/25/46. Assign. Sun Oil Co.

Cable Provided with Polarized Outlets for Seismic Prospecting. A polarized tap for a seismic-prospecting cable having one tap wire forming a pigtail and the other tap wire wound around the cable to form a cylindrical terminal.

U. S. No. 2,582,714. E. H. Meier. Iss. 1/15/52. App. 8/13/49. Assign. Standard Oil Development Co.

Automatic Volume Control Time Response Switching. An output-controlled avc system in which the first kick trips a relay to change the time constants of the circuit which is initially set to have fast onset and slow release and subsequently made to have a somewhat slower onset and somewhat faster release than initially.

U. S. No. 2,582,769. R. L. Congdon. Iss. 1/15/52. App. 6/24/48. Assign. General Instruments Inc.

Seismometer. An electromagnetic moving coil seismometer having a ring-shaped magnet and a central cylindrical magnet and with the coil carrying a disc which moves with slight clearance in a groove to act as a stop.

U. S. No. 2,582,793. E. G. Perry, Jr. Iss. 1/15/52. App. 6/21/48. Assign. General Instruments Inc.

Method and Apparatus for Recording Vibrational Data. A seismograph recorder in which the traces of reflecting galvanometers are recorded on a gray background together with the shadows of string galvanometers, one set of galvanometers being connected to record mixed traces and the other set unmixed.

U. S. No. 2,582,994. J. M. Kendall. Iss. 1/22/52. App. 6/4/43. Assign. Geophysical Research Corp.

Underwater Microphone. A microphone for recording underwater sounds by measuring liquid-particle motion and having a watertight spherical shell with a coil mounted on a projection on the inside of the shell and a permanent magnet elastically suspended in the shell so that its motion generates an emf in the coil.

U. S. No. 2,584,386. D. G. C. Hare. Iss. 2/5/52. App. 5/11/44. Assign. U.S.A.

Band-Pass Filter Network. A low-frequency band-pass filter using R-C filters in series with an amplifying tube having an inverse feedback loop with a sharp minimum-transmission peak at the cut-off point of the series circuit.

U. S. No. 2,585,854. C. B. Scott. Iss. 2/12/52. App. 10/27/49. Assign. Standard Oil Development Co.

Automatic Volume Control for Seismic Amplifiers. An avc circuit for a seismograph amplifier in which the output is sampled, amplified, rectified, and fed to the control grids of a pair of tubes who plate-cathode circuits are part of a voltage divider across the input.

U. S. No. 2,586,706. J. O. Parr, Jr. Iss. 2/19/52. App. 1/12/49. Assign. Olive S. Petty.

Seismic Surveying. A method of underwater seismograph shooting in which the charge is detonated in a balloon or bell, or in a gas pocket formed by a previously-fired gas-releasing charge.

U. S. No. 2,586,731. R. F. Simon and S. N. Heaps. Iss. 2/19/52. App. 3/11/49. Assign. Socony-Vacuum Oil Co., Inc.

Surface Generation of Seismic Waves. A seismograph shooting system in which a loop of Primacord is detonated on the surface of the ground with a number of detonators spaced along its length so that the maximum delay along its length is less than the minimum readable record time.

U. S. No. 2,587,301. W. M. Ewing. Iss. 2/26/52. App. 11/16/45. Assign. U.S.A.

Method of Sound Transmission. A system for long range transmission of sound through sea water in which a sound is generated in the water at the level of minimum sound velocity and observing at

a distant point at the level of minimum sound velocity the occurrence and time spacing of the successive sound impulses received.

U. S. No. 2,588,291. N. H. Ricker. Iss. 3/4/52. App. 10/11/47. Assign. Standard Oil Development Co.

Distortionless Seismic Wave Filter. A distortionless low-pass filter for a seismograph amplifier having a linear phase-shift characteristic and an amplitude-response characteristic of the form $e^{-(f/f_0)^2}$.

U. S. No. 2,590,530. G. M. Groenendyke. Iss. 3/25/52. App. 3/10/48. Assign. Socony-Vacuum Oil Co., Inc.

Seismic Prospecting System. A seismograph prospecting cable and geophone assembly for use in water-covered areas using the geophones as plug members between cable sections and with the seismic detector mounted on gimbals in the geophone housing.

U. S. No. 2,590,531. K. W. McLoad. Iss. 3/25/52. App. 3/10/48. Assign. Socony-Vacuum Oil Co., Inc.

Selector Arrangement for Seismic Prospecting System. A seismograph prospecting cable and geophone assembly for use in water-covered areas using the geophones as plug members between adjacent cable sections and with each geophone containing a gimbal-suspended seismic detector which may be connected into any desired cable for mixing or separate recording.

U. S. No. 2,590,822. J. P. Minton. Iss. 3/25/52. App. 6/28/46. Assign. Socony-Vacuum Oil Co., Inc.

Filter for Seismic Prospecting. A time-actuated automatic filter control for a seismograph amplifier in which the grid bias is changed on tubes forming the resistances in the filter network so as to change the response characteristic with time.

WELL LOGGING

U. S. No. 2,580,457. S. E. Norris. Iss. 1/1/52. App. 6/5/47. Assign. U.S.A.

Measurement Apparatus. An apparatus for measuring the depth of casing in a well having an insulated conducting cable carrying at its lower end a magnet which adheres to and slides down the inside of the casing and a circuit at the surface which indicates electrical continuity from the cable to a connection at the top of the casing.

U. S. No. 2,580,544. G. Herzog. Iss. 1/1/52. App. 12/30/48. Assign. The Texas Co.

Locating Casing Collars in a Well. A casing-collar locator having a neutron source and a neutron detector connected to a resistance-capacity integration circuit whose time constant is commensurate with the time required for the instrument to pass a collar.

U. S. No. 2,581,412. G. Herzog. Iss. 1/8/52. App. 7/6/48. Assign. The Texas Co.

Geophysical Exploration. For abstract see RADIOACTIVITY PROSPECTING.

U. S. No. 2,581,979. M. B. Standing, H. S. Yaplee and M. Macaulay. Iss. 1/8/52. App. 7/18/49. Assign. California Research Corp.

Method and Apparatus for Locating Well Fluid Loss. A device for detecting points of fluid loss from a well into the formation and having at its middle an electrically-controlled source of electrolyte whose arrival in the mud at either end of the device is detected by electrodes and indicated at the surface.

U. S. No. 2,582,314. H-G. Doll. Iss. 1/15/52. App. 6/15/49. Assign. Schlumberger Well Surveying Corp.

Electromagnetic Well Logging System. A multi-coil electromagnetic well-logging system in which the coils have different zones of sensitivity so that cancellation can be obtained over part of the field and the resultant sensitivity made effective over a desired region.

U. S. No. 2,582,315. H-G. Doll. Iss. 1/15/52. App. 9/3/49. Assign. Schlumberger Well Surveying Corp.

Differential Coil System for Induction Logging A multi-coil electromagnetic well-logging system in which the coils have different lateral sensitivity characteristics so that they can be combined to investigate invasion of the formation by borehole fluid.

U. S. No. 2,583,288. J. J. Arps. Iss. 1/22/52. App. 11/12/48.

Well or Borehole Logging. A method of permeability and porosity logging in which a neutron-emitting substance is included in the drilling mud so that it can invade the formation, running a gamma-ray log, and later running a second gamma-ray log after the contaminant has decayed.

U. S. No. 2,583,904. J. M. Thayer, G. Swift and R. E. Fearon. Iss. 1/29/52. App. 7/10/48 and 5/19/50. Assign. Well Surveys, Inc.

Method for Neutron Well Logging. A neutron-gamma-ray logging system in which a first log is run to determine the ratio of random effects to the effect of changing formations and the log repeated with another neutron source which makes the two effects have a ratio of at least one to three.

U. S. No. 2,583,976. J. M. Thayer, G. Swift and R. E. Fearon. Iss. 1/29/52. App. 7/10/48 and 5/19/50. Assign. Well Surveys, Inc.

Method for Neutron Well Logging. A neutron-gamma-ray logging system in which the log is repeated with a different distance between the neutron source and detector so that from a comparison of the logs the effect of random neutron-heavy-particle processes can be determined and eliminated from the log.

U. S. No. 2,585,412. D. Silverman. Iss. 2/12/52. App. 4/29/50. Assign. Stanolind Oil and Gas Co.

Well Productivity Logging. A productivity logging method in which a selective oil solvent heavier than brine is introduced in the well and the brine-solvent interface followed as the well is produced.

U. S. No. 2,586,745. F. N. Tullos. Iss. 2/19/52. App. 11/26/47. Assign. Standard Oil Development Co.

Acoustic Well Logging. An acoustic impedance logging device having a magnetostriction oscillator with an avc network which maintains operations at constant loading.

U. S. No. 2,587,518. J. M. Pearson. Iss. 2/26/52. App. 1/21/49. Assign. Sun Oil Co.

Electrical Logging Method and Apparatus. A method of electric logging through casing in which spaced current electrodes making contact with the casing are moved down the casing and the potential observed between the top of the casing and a remotely-located ground.

U. S. No. 2,588,717. L. O. Goodwin. Iss. 3/11/52. App. 5/25/46. Assign. Stanolind Oil and Gas Co.

Apparatus for Measuring Dips of Well Strata. An electrical dip meter in which potential is measured at three equally-spaced points on the borehold wall and the borehole diameter simultaneously observed together with movement of the instrument along a cable connected to an anchor below the instrument.

U. S. No. 2,588,748. J. A. Niles, N. B. Simpson, H. F. Sturgis, R. P. Vincent and C. W. Ziemer. Iss. 3/11/52. App. 1/22/47. Assign. Stanolind Oil and Gas Co.

Apparatus for Measuring Well Characteristics. A self-recording wire-line-operated electric well flow meter or electric logger in which the electrical quantity being measured is balanced by a step-by-step servo mechanism which also controls movement of the recording stylus over a chart.

MISCELLANEOUS

U. S. No. 2,583,276. H. W. Patnode. Iss. 1/22/52. App. 4/20/50. Assign. Gulf Research & Development Co.

Method of Determining Formation Factor of Irregular Rock Samples. A method of determining the electrical formation factor of formations traversed by a drill from resistivity measurements on drill cuttings when immersed in a saturating electrolyte and when immersed in the electrolyte with its resistivity altered by suspending in it either conducting or insulating particles.

U. S. No. 2,583,284. M. R. J. Wyllie and G. A. Hogg. Iss. 1/22/52. App. 4/20/50. Assign. Gulf Research & Development Co.

Method for Determining a Parameter of Earth Formations Penetrated by a Borehole. A method of determining the electrical formation factor of formations traversed by a drill from resistivity measurements on drill cuttings when immersed in a saturating electrolyte and when immersed in a non-wetting electrolyte.

U. S. No. 2,588,210. O. W. Crisman and A. J. Teplitz. Iss. 3/4/52. App. 11/18/49. Assign. Gulf Research & Development Co.

Method of Locating Leaks in Well Bores. A method of locating points where fluid is leaving a well by mixing with the well fluid a fibrous or lamellar material which has been made radioactive and which will lodge in the leak channel so that the leak may be located with a radioactivity detector.

SELECTED LIST OF U. S. PATENTS ISSUED DURING THE FIRST QUARTER OF 1952.

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Third World Petroleum Congress, The Hague, 1951, Proceedings, Sec. I, Geology—Geophysics, E. J. Brill, Leiden, Netherlands, 665 pp., $32.00.

Section One of the proceedings of the Third World Petroleum Congress held at The Hague in 1951 is entitled "Geology—Geophysics." In a certain sense this title is misleading, in spite of the fact that most of the forty-seven articles do have the word "Geology" or "Geophysics" in the title. Nevertheless, a fair proportion of the papers are concerned with subjects that only a decade or so ago would have looked out of place in a compendium of this type. The diversification of subjects that are presented is a strong indication that the present day geologist and geophysicist must have an understanding of many subjects in addition to the fundamentals of his field in order to keep abreast of trends and improvements in the broad field of petroleum exploration. In order to do so, such subjects as radioactivity, bacteriology, the telluric current phase of electrical prospecting, the relationships between the chemical constituents of various types of crude oil, and the geological conditions under which they are found must be considered to an ever-increasing extent.

This volume cannot be reviewed in the usual sense of the word because no one can be expected to be thoroughly familiar with the fundamentals and pertinent literature of the diversified subjects discussed in the forty-seven papers to the extent that is generally expected of one who is given a book or periodical on a specific subject for review. Conventional comments on each paper by one individual would be rather pointless and could, at best, fall in the category of an abstract rather than a review. Therefore, emphasis in this discussion will be placed on the geophysical papers, not only because the reviewer is more familiar with this subject, but because the review is being published in *Geophysics*.

The majority of the articles deal with the regional geological characteristics of oil and gas-producing areas throughout the world, with emphasis on Europe and the Middle East. These papers

constitute an important source of information on the structural, stratigraphic, and oil-producing potentialities of areas such as the western part of the United States and Canada, Venezuela, Mexico, Turkey, Southwest Persia, the Adriatic geosyncline, the Po Basin, Trinidad, Germany (especially the northwestern and Emsland area), and the Aquitaine Basin. The illustrations accompanying these papers are generally of excellent quality, particularly from the standpoint of showing the structural, stratigraphic, and geological relationships. The scales shown are well-suited for the areas under discussion so that sufficient data can be presented without loss of detail. A number of excellent stratigraphic sections are also included. One feature of this volume which adds much to its usefulness in evaluating the contents and ideas found in these papers is the presentation of both the printed and oral discussions provoked by the paper and the rebuttal of the author. Information present in these discussions can frequently serve as criteria for the evaluation of the paper by the reader, particularly when it is known that many of the persons involved are authorities on the particular geological area or on the theoretical aspects of the subject.

Approximately a dozen papers describing the results of theoretical geophysical investigations or areal surveys are presented with examples from each of the major branches of geophysics, reflection, refraction, gravity, magnetic, and telluric current methods. The majority of the papers discuss seismic prospecting with emphasis on the propagation of seismic waves and areal surveys in southwest Persia and Western Germany.

Included in the group of papers on regional geology are several which could also be classified as case histories of smaller geographic units, such as individual or closely related oil fields. Some of these will be discussed briefly in later paragraphs. In addition to the papers dealing primarily with geophysics, a number of the geological papers contain corroborating geophysical data, for example, those by Jobli and by Facca, in which the results of dip-shooting and continuous-profiling are discussed and illustrated. A paper by G. B. Moody on oil fields in the western part of the United States, in which his criteria for physiographic provinces are taken from a map by Fenneman, contains an interesting summary of the chief methods of oil exploration leading to six different periods at which discoveries of oil fields reached a maximum. These methods start in 1900 with seepage drilling, and continue through to 1948, at which time re-appraisal of geologic data is given major credit for the successes beginning with that period. The paper by DeJuana and Rodriguez is characterized by a number of excellent small scale maps, correlation charts, columnar sections, and data on the producing and geologic characteristics of forty-six oil fields found in these areas. In J. E. Smith's article on the Cretaceous limestone producing areas of Venezuela, excellent photographs showing fracturing in a number of limestones are presented. These illustrations, and the accompanying discussion on production from fractured horizons, should be of particular interest to geologists and petroleum engineers at this time, in view of increasing production from the Spraberry of West Texas and other reservoirs of this type. The quality of several maps found in Alvarez's discussion of the geological significance of the distribution of the Mexican oil fields adds much to the value of this paper by giving the reader a clearer insight into the trends of these oil fields and their relationship to extensions into the United States. As the title would indicate, the paper, "The Tectonic Framework of the Far East and Its Influence on Petroleum," by G. F. Kaufmann, presents a number of provocative ideas to the reader. They are discussed primarily in terms of broad generalizations and are accompanied by a large number of maps and cross sections drawn on a global scale. As might be expected, a paper of this type gave rise to a considerable amount of discussion. In fact, the discussion section is the longest for any of the papers, and was participated in by geologists such as Vening Meinesz, Van Benmelen, and Umbgrove. The bulk of the criticism deals with the controversial geotectonic section of the paper. However, the author includes a rather comprehensive bibliography of forty-seven pages, which should be a great aid, in combination with the maps, for anyone having the time and the inclination to evaluate the concepts presented. A very detailed and comprehensive tabular summary of stratigraphic and paleontological conditions in six specific localities in the Middle East does much to increase the value of F. R. S. Henson's scholarly paper on the observations on the geology and petroleum occurrences of the Middle East. The information presented in the paper by P. E. Kent, et al., on stratigraphical exploration surveys in Southwest Persia is very useful in furnishing additional

information on the geology of the Middle East, using an approach similar to Henson's. A section is included on the results of geophysical surveys in this area, using refraction seismic methods, to determine indirectly the depth of the Asmari limestone oil reservoir formation. Once the depth to the base of the middle Cretaceous limestone is determined, its thickness is obtained from an isopachous map, and this value then is subtracted to obtain the depth to the Asmari limestone reservoir. In addition to the usual geologic discussion found in a case history, accompanied by a number of excellent cross sections and production and chemical data, a paper by D. C. Ion, et al., on the Agha Jari oil field of Southwest Persia contains several excellent aerial photographs. These are very helpful in studying the local structural conditions.

The paper by Jaboli entitled "Le Gaz et le Petrole dans la Plaine du Po," in addition to describing in considerable detail the geological methods used in the exploration history of the Po Valley, discusses the use of seismic reflection data with emphasis on dip-shooting and continuous-profiling. The results of this seismic work are illustrated in seven cross sections with the geologic information superimposed. Excellent examples of major types of subsurface geologic conditions, including angular unconformities, anticlines, faults, monoclines, as well as combinations thereof, may be seen in these illustrations. It is interesting to note the effect of American seismic methods in exploration geophysics in other parts of the world as exemplified in this article, not only from the standpoint of their adaptation, but also the impact on linguistic terminology. The article is written in French, but apparently there is no adequate translation for dip-shooting, because this phrase occurs in English within quotation marks. Similarly, the geologic terms, "traps" and "pinch-outs," also appear in English.

Digressing for a moment in this regard, it is interesting to note minor changes in usage and nomenclature appearing from time to time throughout a number of articles in this volume. For example, the term "pucker" is used in the article by D. C. Ion, et al., in the paper on the Jagha Jari Oil Field in connection with the phrase "surface axis of frontal pucker." Similarly, the word "isopachyte" occurs in an article by P. E. Kent on stratigraphical exploration surveys in Southwest Persia, on maps, and in the text in such phrases as "isopachyte and facies map" and "alternative isopachytes for the Pabdo-Kazerun area." Admittedly, this word does not have standard usage in the American literature, appearing frequently as "isopachous," as well as "isopach," but now for variety, the term "isopachyte maps" can also appear, using this article as precedent.

The case histories of the three gas-bearing sands in the Po Valley, by Facca, in addition to carrying the usual information regarding geologic reservoir and production characteristics, including structural and isopachous maps, contain two cross sections for two fields showing the results of dip-shooting in that area to a depth of 3,000 meters. Two closely related articles by E. Pera and L. Faleschini are found between pages 267 and 295 and are concerned with natural gas in Italy, including such factors as the chemical composition and characteristics of natural gas fields in Italy, as well as economic factors involved in the production and consumption possibilities of natural gas in that country. The economic data includes a historical summary of production and consumption of hydrocarbons beginning in 1860, and an interesting economic study in the pipeline transportation of gas in terms of "the unit cost of connection (Cu)"; i.e., the cost of a pipe divided by the quantity of gas transportable in that pipe in a given unit of time. This concept is expressed algebraically, and the results shown graphically in two figures on pages 294 and 295, with the unit cost of connection as a function of the distance from a center of production, as well as the unit of cost for certain centers of consumption in northern Italy. The article on the geology of the Aquitaine and its petroleum possibilities, written in French by Y. Gubler, et al., contains a number of small-scale block diagrams and structural cross sections, as well as some illustrations showing the relationship between facies changes and structure. The particular type of block diagrams in this paper are especially well-suited to convey the necessary information to the reader about an area characterized by its extreme structural complexity.

A series of three papers beginning on page 335, and ending on page 389, all have one thing in common; namely, a discussion in varying detail of the relationship between the chemical and physical characteristics of the several types of oil found in these areas with the horizons from which they were produced. The impression gained by analyzing the information presented in these papers is

that the relationship between the geologic age, depth of producing horizons, and the chemical characteristics of the crude oil is very irregular. The reason for this lack of correlation among these parameters is sought for in the effect of catalytic action of the various mineral constituents comprising the producing horizons from which the oil is obtained. For example, it is pointed out in the discussion of the G. C. Facca, et al., paper on Italian crude oil analysis, that oils found in limestone differ in physical and chemical properties from those produced from fractured sandstones and marls, even though they may occur at the same depth. The amount of detail in this paper, as well as in the one by K. W. Barr, et al., on the Forest Reserve Field of Southwest Trinidad, and in H. D. E. Loegter's paper on "The Genesis of Oil Deposits in the Emsland Area of Germany," enables the reader to arrive independently at his own conclusions with respect to this problem. The Loegter paper also contains an interesting use of a paleotectonic map of Laramide folding in the Emsland Area. This type of map, combining tectonic and stratigraphic, including isopachous lines, and structural, data, is not used widely at the present time by many geologists in this country. It should be noted in the discussion of these three papers that the relationship between chemical composition and migration factors has not been neglected.

Another series of three related papers, beginning on page 401, and ending on page 438, deals with the origin of petroleum, in which such diverse factors as conditions favoring the preservation of chlorophyll in marine sediments, the contribution of bacteria to the origin of oil, as well as the part played by radioactivity in its genesis are discussed. The paper on the preservation of chlorophyll is by M. Brongersma-Sanders, and contains an appendix written by W. G. Aldershoff, describing the determination of the chlorophyll content of a Walvis Bay sediment. The authoress is well known for her investigations regarding the origin of petroleum, including the possibility of mass mortality of organisms caused by a number of meteorological and oceanographical conditions. In addition to her original investigations in the field and laboratory, she has also compiled comprehensive bibliographies on this subject, one of the most recent of which appears in an article entitled, "The Importance of Upwelling Water to Vertebrate Paleontology and Oil Geology," published in 1948 in the periodical Kon. Ned. Ak. Wet., (Tweede Sectie), Dl. XLV, No. 4, p. 1–112, 1948. A recent closely related reference to this subject written by T. S. Austin and Helen Ladou Hayes appeared in the December, 1951, issue of the *Texas Journal of Science*, and is entitled "The Distribution of Discolored Sea Water."

The mechanism of mass mortality as a possible cause for the accumulation in sufficient quantities of oil-source material is receiving increasing attention by petroleum geologists. Therefore, the paper under discussion is of particular interest because the hypothesis is developed that, "Hypertrophic conditions in the sea probably are the main cause for the origin of oil and are far more important than persistent stagnation." In this connection, "distinctive features of hypertrophic conditions are: a frequent occurrence of thick water bloom (particularly of red water) and of mass mortality of vertebrates and invertebrates." These conditions are not confined to the oceans, but may also occur in inland seas under the proper "abnormal" ecological conditions. This paper concludes with a bibliography of 58 references pertaining to this subject. C. E. Zobell, in his discussion of the contributions of bacteria to the origin of oil, again points out that "biochemical and ecological versatile bacteria capable of catalyzing a good many reactions involving organisms and inorganic compounds occur abundantly in Recent marine sediments." The chemical, physical, ecological, and bacteriological factors involved in this contention are presented in broad outline. This very fundamental and, to a certain extent, provocative paper caused considerable comment involving a discussion by seven people who, for the most part, agreed with many of the points made in this paper.

The paper by I. A. Breger and W. L. Whitehead, in which radioactivity and the origin of petroleum are discussed, presents the available results that have been obtained at the Massachusetts Institute of Technology by research activities conducted since 1942 under the sponsorship of the American Petroleum Institute. The purpose of this project is to investigate the effect of radioactivity on transforming marine organic materials into petroleum. Thus far, it has been possible to convert fatty acids into aliphatic hydrocarbons and to produce gaseous hydrocarbons found in association with crude oil. In addition, the conversion of naphthenic acid into a cyclic hydrocarbon by means of alpha particle bombardment has been demonstrated, and investigations have been conducted to

determine the radioactivity of several important geologic horizons associated with petroleum. Studies are currently underway to determine the relationship between organic matter and radioactive elements in organic marine shale. This paper also caused considerable comment and is discussed by eight persons, some of whom disagree with the statement "oil was never generated in limestone," citing examples from Venezuela and the Middle East.

Progress made in recent years in the study of sediments from the standpoint of shifts of biofacies, in isochronous correlation studies, and in new methods of studying the sedimentary characteristics in rock is presented in a series of three related papers beginning on page 428 and ending on page 461. In addition, the use of micro-facies for stratigraphic correlation, particularly in the East Aquitaine area, and the application of a recently developed method to improve criteria for the recognition of marker beds in predominantly calcareous sections by the use of lithographic data are also included. The papers are all characterized by the presence of excellent illustrations, including cross sections and subsurface logs which facilitate the study of the information and ideas developed in the text.

Several papers, in which the emphasis is on the use of paleontology and sedimentology in the search for productive horizons, are also found in this volume, including one entitled "Sedimentology and Petroleum Geology" by D. J. Doeglas; a paper in French by A. Lombard, entitled "Methode D'Etude et D'Interpretation des Series a Sedimentation Calcaire Predominante"; "The Tertiary Pelagic Foraminifera" by T. F. Grimsdale; "On Some Paleocene and Eocene Larger Foraminifera of Western Venezuela" by B. Van Raadshoven; and a paper by M. Lys and N. Grekoff entitled "Microfaunes du Cretace Superieur et du Paleocene, Leur Utilisation en Afrique Equatoriale Française."

The last eleven papers in this volume, starting on page 497 and ending on page 653, deal directly with the use of geophysical methods for petroleum, including both theoretical and practical aspects of seismic and telluric current prospecting. The papers in the theoretical group include "The Precision of Travel-Time Curves in the Seismic Method of Geophysical Surveying" by A. A. Fitch and E. H. Lloyd; "The Form and Laws of Propagation of Seismic Wavelets" by Norman Ricker; "The Laboratory Studies of Transient Electric Waves" by S. Kaufmann and W. L. Roever; "Graphical Evaluation of the Anomalies of Gravity and of the Magnetic Field Caused by Three Dimensional Bodies" by Fritz Gassmann; "Une Modalité D'Application et D'Interpretation de la Methode Sismique" by Jose Cantos; and "Interpretation Quantitative Des Mesures en Prospection Par Courants Telluriques" by V. Baranov.

Papers dealing primarily with field surveys include those by D. T. Germain-Jones entitled "Seismic Surveys Over Asymmetrical Structures in Southwest Persia"; "Applied Geophysics in West Germany During the Last Five Years" by Hans Cloos; a paper by T. H. Krey and B. Helwich entitled "Les Reflections à L'Interieur des Domes de Sel et Leur Importance Pour Les Recherches de Petrole"; and a paper by L. Migaux entitled "Dix Ans D'Application de la Methode Tellurique." In addition, a paper dealing primarily with the interpretation of regional gravity data entitled "Isogam Maps of the Caribbean Area and Surroundings and of Southeast Asia" by J. W. DeBruyn is presented.

The last paper of this series contains four very interesting maps, two for each of the areas discussed, one showing gravity data and the other bathymetric and volumetric information. The maps are drawn on a scale of 1:10,000,000 with an isogam interval of 25 milligals used for those showing gravity. The Caribbean isogam map is based upon Hayford-Bowie isostatic anomalies, using a depth of compensation of 113.7 km., and the Southeast Asia map depicts regional isostatic anomalies using Vening Meinesz' system which he described in Volume II of his "Gravity Expedition in the Sea." For purposes of comparison, attention is called to the Bouguer map of the southern part of the United States discussed by L. L. Nettleton in Volume XIV, pages 275–287, appearing in *Geophysics*. Examination of these two maps reveals that the isostatic reduction shown in DeBruyn's map does not differ substantially from the Bouguer interpretation. The author discusses the high Bouguer and isostatic values existing at the mouths of the Mississippi and Rio Grande in Chapter Three. He also points out that the deltas of five large Asiatic rivers, including the Indus, Ganges, and Yellow River, all have positive Bouguer anomalies. The several major geotectonic features asso-

ciated with the gravity data are discussed in some detail whenever the latter information is available in sufficient quantity. Details regarding the source of the gravity data on land and at sea, together with pertinent bibliographical reference, are presented in two appendices. As might be expected, a paper of this type aroused considerable discussion, and the remarks of Vening Meinesz, Umbgrove, Nettleton, and Hess appear in the discussion section.

The paper by Ricker dealing with the propagation of seismic wavelets may be considered essentially as a synthesis of his investigations on the fundamentals of seismic wave propagation that have appeared from time to time in numerous publications in *Geophysics*, the *Bulletin of the Seismological Society of America*, and the *Transactions of the American Geophysical Union*. It gave rise to considerable discussion and was commented upon by D. T. Germain-Jones, C. H. Dix, T. Krey, and N. D. Smith. In the course of these discussions, the value of the information presented in this paper towards the solution of some of the fundamental problems of seismic wave propagation was emphasized, and the need for additional research in this field was mentioned. The information presented in the paper by Kaufmann and Roever, dealing with the results of a laboratory investigation of transient electric waves, also included fundamental data regarding the characteristics of waves as they are propagated through various media. Evidence presented in the paper indicated that it is feasible to use model experiments of this type in studying these problems, and that the results are of practical interest. A number of illustrations of wave forms at various distances from the spark gap source is included. The problem involved in conducting seismic surveys over asymmetrical structures in Southwest Persia is discussed in some detail by D. T. Germain-Jones. One of the major difficulties encountered was the marked discrepancy between the results of refraction and reflection surveys in delineating the structural axes in this area. In discussing these problems and the methods used to attempt to solve them, an excellent series of illustrations, including actual records and detailed structural cross sections, are presented. In addition, a stratigraphic section ranging from the lower Cretaceous to the Pleistocene is presented. Its value to seismic studies for this area is enhanced by including the seismic velocities obtained in each of the representative horizons. Even a cursory examination of these data will demonstrate some of the reasons for the difficulties encountered in seismic prospecting in this area, not only because of the absence of continuously increasing velocity with depth, but because of the wide range in velocities encountered in a number of formations. The article by Hans Cloos, reviewing the results of applied geophysics during the last five years in Western Germany, contains a large number of excellent illustrations of seismic records and reflection survey profiles. Some of these are correlated with geology to demonstrate certain points made in this paper. The same comments apply substantially to the paper by T. H. Krey and V. Helwich entitled "Les Reflections a L'Interieur des Domes de Sel et leur Importance pour les Recherches de Petrole."

Two papers dealing primarily with the interpretational aspects of telluric currect prospecting conclude this volume. They are by L. Migaux and V. Branov and are entitled "Dix Ans D'Application de la Methode Tellurique," and "Interpretation Quantitative des Mesures en Prospection par Courants Telluriques," respectively. The number of references appearing in the literature during the past few years on telluric currents is increasing. The first paper in this group is of particular interest because it reviews, using essentially a case history technique, the results of this type of geophysical prospecting in a number of countries in Europe as well as in Africa. A brief review of the basic principles of this method is also given although much the same information can be found in English in a paper by Boissonais and Leonardon appearing in *Geophysics* in 1948.

An attempt is made to interpret quantitatively some of the data available from telluric current prospecting although the author limits himself to the two-dimensional case in order to avoid cumbersome computations. However, the problems inherent in quantitatively interpreting these data are very similar to those encountered in gravity, magnetic, and electrical prospecting. In addition, the rather simplified theoretical assumptions cannot begin to take into account the various lithologic and structural inhomogenieties found, particularly in the shallow portions of the earth's crust. A similar analysis is described by Tuman in an article published in English in *Geophysics* in 1951.

One cannot help but be impressed by the broad diversification of subjects pertinent to the oil finding profession that are presented in this compendium. The conclusion is reached, after perusing

this volume of more than 655 pages, entitled *Geology-Geophysics*, that modern day oil finders can no longer afford to over-specialize in any one of the numerous ramifications of this field of endeavor if the successes of the past are to be repeated and even improved upon in the future. The wide variety of subjects discussed adds validity to the increasing use of the term "oil finders" for those engaged in the exploration for petroleum, rather than such "narrow" titles as geologists, geophysicists, paleontologists, petrologists, bacteriologists, and oceanographers.

To summarize the value of this book to the petroleum exploration profession in a concise statement, it may be said that, if all other literature pertaining to this field were to be destroyed and only this book remained available to future generations, it would serve not only as a starting point for additional knowledge, but it would acquaint them with the tremendous progress that has been made in the techniques of petroleum exploration during the past two decades.

RICHARD A. GEYER

Plane Table Mapping, by Julian W. Low, Harper & Brothers, New York, 1952, 365 pp., $5.00.

In his preface, the author cites two objectives as foremost in the assembling and arranging of the the text materials: the first, "to place in the hands of teachers and students an elementary text suited to beginning courses in field mapping," and the second, "to assemble a large number of methods adaptable to certain types of mapping in order to make the book more convenient for the man in the field."

This field manual goes beyond the achievement of these two objectives and will be a useful and important addition to the library of the geophysicist and geologist. The book, similar in size and weight to the familiar surveyor's field book, opens with an explanation of spatial relationships of features on or near the earth's surface and the measurement of such relationships. In orderly and understandable fashion, plane table instruments are described and the proper setting up, leveling, and orienting of them explained in detail. Traversing, differential leveling, and indirect (trigonometric) leveling are naturally a part of the chapter on elementary plane surveying. The chapter dealing with plane table triangulation and those covering the various types of mapping, while written for the beginner, will improve the plane table knowledge of even the expert. Ample instructions for the adjustment, care and repair of plane table instruments are a part of this book.

During the twenty some-odd years this reviewer has been in contact with various geophysical field crews, he has been appalled, on numerous occasions, at the frequency of plane table surveying errors due to insufficient knowledge of instruments and methods on the part of the surveyor. Quite often the supervisor, the party manager, and the party chief are not qualified to evaluate the skill of the surveyor nor to correct any misuse of instruments or methods. A copy of Julian W. Low's *Plane Table Mapping* on each field crew using the plane table for surface control would be invaluable in relieving any such situations. The careful study of this manual by the surveyor and party chief would result in improved accuracy of topographic data and a subsequent improvement in the accuracy of the end product, the geophysical interpretation.

IRVING M. GRIFFIN, JR.

The Sea Around Us, by Rachel Carson, Oxford University Press, New York, 1951, 230 pp.

The Sea Around Us is probably the first book having any relation to geophysics which has ever achieved the status of a best seller. At the present writing (April 14, 1952), it has been at the top of the non-fiction lists for thirty-two weeks.

When a book on a scientific subject sets a record like this, it is understandable that some might be suspicious of the book's authenticity, having some doubts whether such success can be attained without a dangerous amount of popularization that takes liberties with the facts. The fact is, however, that the book is good responsible scientific reporting and at the same time the rare type of good literature that is likely to become a classic.

The Sea Around Us is the story of the ocean in all its aspects, told by a marine biologist, who has carefully studied the current literature of physical as well as biological oceanography, in a form not only understandable but most appealing to the layman. Oceanography, like most other sciences, has its controversial issues. It is not likely that every professional investigator of the ocean will agree with all of Miss Carson's conclusions or acknowledge that she has given full weight to evidence supporting interpretations that she rejects. No experts in the field, however, will deny the essential correctness of her information.

Exploration geophysicists are looking more and more to the borders of the oceans as a source of oil and might well benefit from the kind of knowledge of the sea which this book offers the reader. Even outside the professional motivations, all who have any interest in natural science and who want the pleasure of reading the English language at its best are urged to examine this book.

MILTON B. DOBRIN

Energy Sources—The Wealth of the World, by Eugene Ayres, Charles A. Scarlott, McGraw-Hill Book Company, Inc., New York, 1952, 344 pp.

This book is an elaboration of the paper, "Major Sources of Energy," presented at the American Petroleum Institute's Chicago meeting in November, 1948. The demand for reprints was so great that, after almost 10,000 copies had been requested, it was decided to make this subject available in book form. This is understandable, because it may be considered as being a compendium of the most recent facts and figures available at the time of publication on known sources of energy that are, or could be, used by man. The information includes critical analyses of various types of energy resources and many energy conversion processes, as well as enumerations of the major factors responsible for energy losses. In addition, many tables and graphs of a statistical and interpretative nature are presented. No possible source of energy is omitted. Chapters are included on energy from the sun, wind, tide, rain, atomic nuclei, and vegetation, together with the more conventional forms of fossil fuels.

The historical approach to the problem is presented also in a very interesting manner, with emphasis on early production of fossil fuels in various portions of the world extending as far back as 6000 B.C. Prior to 640 B.C. attempts were made to utilize solar energy by optical concentration. Concave mirrors of bronze lined with silver foil were used to focus the rays of the sun. Starting with information of this character, the book continues chronologically to the newest innovations in energy conversion, such as the heat pump and recent improvements in solar and nuclear power plants. A large number of interesting facts are included in a number of chapters, as for example: "When the Pilgrims made their historic voyage on the Mayflower, British Patent Number 15 was issued for the coking of coal"; "An oil well was completed at Modena, Italy, in 1640 which flowed moderately for nearly 200 years"; "In 1692, the Spaniards were granted oil concessions in Peru"; "The first commercial mining of bituminous coal in North America, after the Hopi Indians, was in Virginia in 1730."

In addition to a very complete bibliography, the book contains two appendices which add much to its usefulness from the standpoint of summarizing some of the outstanding facts, generalizations, and predictions discussed in the earlier chapters. Also they make available a number of conversion factors used in fuel and power studies. Some of the more interesting generalizations in Appendix I include: "All the fossil fuel produced in the world up to 1900 A.D. would satisfy the present world economy for only about five years, although the peak of fossil fuel production in the United States may come between the years 2025 and 2111 A.D."; "Theoretically, tidal energy could supply about one-half the world's needs, but we are unlikely to obtain more than 0.3% of this potential"; "Brazil's estimated total oil reserves would last only three days in the United States." The page references for the bases for these facts and predictions are also included after each statement.

This book is one of few about which it may be said that it combines the features of an authoritative reference work for the most recent statistical and factual data on sources of energy as well as

the presentation in a most interesting and readable manner of a summary of man's diversified attempts to harness energy throughout the ages.

RICHARD A. GEYER

Die Wassererschliessung, by Drs. Hans Schneider, Christian Truelsen, and Heinrich Thiele, Vulkan-Verlag Dr. W. Classen, Essen 1952, 421 pp., 68 DM.

This volume, published under the auspices of the German Society for Gas and Hydrological Engineers, represents a definite contribution toward furthering the science of applied hydrology in many of its phases, including the exploration for and production of water resources for population centers and industry. It is divided into three sections. The first deals with the principles of hydrology, including the geologic, chemical, petrographic, and production aspects both from the empirical and theoretical standpoints. It is written jointly by Drs. Hans Schneider and Christian Truelsen, and comprises the initial 284 pages of this volume. The second part is of particular interest to those geophysicists interested in the use of electrical prospecting methods in the search for subterranean aquifers. This discussion, covering 90 pages, again includes both the practical and theoretical aspects of this subject. The three sections are well illustrated, containing a total of 440 figures in Part I, and 115 in Part II. An extensive bibliography of almost 400 references is included, together with 8 pages of conversion tables pertinent to applied hydrological problems. The third part is unique for a book of this type in that it consists of 41 pages of advertisements by a group of equipment and supply companies serving industrial hydrological projects. However, the advertisements for the most part are not confined to the conventional commercial type, but contain technical information which should be useful to many applied hydrologists.

An interesting feature of Section I in the concluding chapter of 37 pages is the presentation of the solution of several industrial ground water problems by the case history method. This chapter serves to synthesize the previous empirical and theoretical discussions relative to the geological, geochemical, and petrological aspects of ground water investigations.

The chapter on geo-electric prospecting is well written, and the information is presented in considerable detail both from the standpoint of basic fundamentals as well as application to exploration problems. A large number of tables giving the electrical characteristics of the more commonly occurring aquifers, particularly the relatively unconsolidated types, are very helpful and fall in the category of new material available in this section. The same applies to the detailed and numerous graphs showing the relationships between the chemical properties of the subterranean waters and their electrical conductivity, with emphasis on the chlorites, sulphates, and bicarbonates. This section also contains two pages in which an attempt is made to present a short summary of all the geophysical prospecting methods and their applicability to the search for ground water, as well as for other economic substances. In this connection, it is interesting to note that the application of the various geophysical methods to the search for possible petroleum bearing structures is not mentioned once, and under the heading of instruments used in magnetic methods only the Schmidt field balance is listed. No mention is made of the other types of instruments used in magnetic prospecting including the airborne magnetometer. Although the author, Dr. Heinrich Thiele, includes a comprehensive bibliography of 169 references, only a brief reference to Dr. Voelker Fritsch's many publications is made, namely, his book appearing in 1949, entitled, "Grundzeuge der angewandten Geoelektrik." Similarly, no mention is made of the electrical techniques used in exploration geophysics described in the literature by Lewis, Evjen, Klipsch, and Blau. In addition, the possibility of using telluric current methods as described by Boissinais and Leonardon is also omitted; and in the discussion of the fundamentals of geo-electrical prospecting, no mention is made of anisotropic effects which frequently play an important part in the interpretation of data obtained from field surveys.

One of the major problems of a book of this type, according to the introduction, is how to bring together the available information on the fundamentals of ground water and applied hydrology in a manner which will stimulate discussion and further research on the many practical and scientific

problems with which this profession is now faced in order to hasten the day of their solution. The reviewer believes that this objective has been achieved to a remarkable degree, and it is unfortunate that language barriers will preclude the widespread use of this book among practical hydrologists and ground water personnel in this country.

RICHARD A. GEYER

Geophysical Surveys on the Bahama Banks, by C. S. Lee, *Journal of the Institute of Petroleum*, Vol. 37, No. 334, Oct. 1951, pp. 633–657.

This paper, which discusses the geophysical work done in the Bahamas in recent years, is the first general study to appear. The author points out that interest in the Bahama Banks was primarily the result of oil discovery in Florida and oil shows in Cuba. Geophysical work in the Bahama Banks was also part of the general project of investigating oil prospects in the Caribbean. In 1945, several major companies applied for concessions, and ultimately they were granted to local representatives of Anglo-Iranian, Shell, Gulf, Superior, Standard, and Central Mining Investment Corporation. This paper is intended to record the methods used by British Bahamian Oil Development, Ltd., (a subsidiary of Central Mining Investment Corp.) and its contractors, and to relate the results to such geological and topographical features as are apparent.

Gravity work in the BBOD concessions was conducted in the conventional way on land, by boats and tripods in shallow waters, and by boats and diving bell in the deeper and open waters. Sextant triangulation was used in shallow areas, and radar ranging was used in deeper areas for horizontal control. Gravimeter observations were tied into pendulum stations on land in order to have a complete gravimetric picture to assist in studying the isostasy of the area. Many points of the regional picture were contributed by pendulum observations previously made in a submarine operating in some of the very deep waters of the area. A map showing the significant Bouguer gravity anomalies of the Bahama Banks is given, as well as detailed maps of the Abaco, Eleuthera, and Ragged Island areas. Contour interval of the detailed maps is one milligal.

A limited amount of seismic work was carried out in the Ragged Island concession, and both refraction and reflection methods were used. The reflection method was more commonly employed, and all records were mixed. Straddle spreads were used with the geophones resting on the sea bed. Charges varied from 2½ pounds to 800 pounds, depending on the nature of the survey. No seismic maps are shown.

A magnetic survey covering about 130 square miles was run in the Ragged Island concession. The magnetic detector was encased in a torpedo and towed beyond the ship during the survey. Details of the technique are described but no magnetic maps of the survey are given.

With the gravity data available and the known geology of the area, Dr. Lee reviews the theories of the structural and sedimentational processes, bringing them up to date in light of the new data. He reports that authorities on the Bahamas, from Suess in 1885 to Hess in 1933, have attempted to give a single explanation for the geologic origin of the island. Schuchert, in 1934, expresses his explanation in two parts. He believes that the older, the northern part of the Bahamas, belongs to the Cuban foreland whereas the younger, the southeastern part of the archipelago, grew as a slightly crescentic Bahamian volcanic arc. Dr. Lee believes the evidence presented in his paper indicates a much more complicated origin. He goes into considerable detail to explain the relationship among physiography, gravity values, structure, and sedimentation in the Bahamas.

This paper is well illustrated and contains a tremendous amount of information that should be of interest to the geologist as well as the geophysicist.

EUGENE W. FROWE

A Note on Air Coupled Surface Waves, by Norman A. Haskell, *Bull. Seismological Soc. Am.*, Vol. 41 1951, pp. 295–300.

This paper might have been a rather significant contribution to seismic wave theory if it had

not been subjected to the misfortune of a sixteen-months' lag between its submission and its appearance in print. During this interval, another paper, by Press and Ewing,* appeared which represents a considerably more definitive advance in the development of the air-coupling concept. In spite of this, the two papers furnish an interesting illustration of how two workers in the same field independently reach similar conclusions when starting with the same body of data.

In both cases, the starting points were: (1) the experimental observation by Press and others that an air explosion over floating ice gives a single-frequency wave, the frequency being that for which the phase velocity of flexural waves is the same as the speed of sound in air, and (2) their deduction that this wave results from coupling between the proper flexural wave component in the ice and the compressional wave traveling at the same speed in the air. The next step which both took was to hypothesize that air-coupled waves would be observed when a disturbance in air excites any kind of surface wave having a vertical component of motion and a phase-velocity that equals the velocity of sound in air at some frequency.

Press and Ewing show that Rayleigh waves, often the most prominent constituent of "ground roll," have the correct type of dispersive curve for the production of air-coupled Rayleigh waves; and the frequency is predictable, using explosions in the air. They develop the theory for this type of wave and give experimental results that check their theory quantitatively.

Haskell points out that one should expect air-coupling with "ground roll," but never mentions that dispersive Rayleigh waves should give rise to the coupling or that the source of excitation should be in the air. Actually, he implies that compressional or shear body waves should result in air-coupled waves if their speed is equal to the speed of sound in air although body waves of this type are not dispersive.

As experimental evidence of air-coupling, Haskell suggests that the "H" wave reported by Howell† is an air-coupled wave. This appears unlikely for several reasons. In the first place, the explosions from which Howell's wave was recorded were at least 20 ft deep so that air waves could not have been excited with any efficiency. In the second place, the "H" wave does not have the proper particle motion for Rayleigh waves. No evidence has ever been obtained that the "H" wave, whatever its nature, is dispersive, as Rayleigh waves are. Finally, the onset of Howell's "H" wave is not generally at the time when an air wave would arrive although this would be required with dispersion of the Rayleigh-wave type.

It is hoped that these two publications on air-coupled waves will stimulate further investigation of this type of phenomenon, especially as it applies to air shooting of the Poulter type.

MILTON B. DOBRIN

* Frank Press and Maurice Ewing, "Ground Roll Coupling to Atmospheric Compressional Waves," *Geophysics*, Vol. 16, 1951, pp. 416–430.

† B. F. Howell, Jr., "Ground Vibrations Near Explosions," *Bull. Seismological Soc. Am.*, Vol. 39, 1949, pp. 285–310.

A SCRUTINY OF THE ABSTRACT*

KENNETH K. LANDES†

ABSTRACT

The behavior of editors is discussed. What should be covered by an abstract is considered. The importance of the abstract is described. Dictionary definitions of "abstract" are quoted. At the conclusion a revised abstract is presented.

Presumably new editors, like new senators and small children, should be seen and not heard. But unfortunately the Association has elected (the electorate had no choice) an editor who is a nonconformist. For many years I have fretted over the inadequate abstract, and now perhaps I can do something about it—but not by keeping quiet.

Many of the abstracts appearing in the publications, including the meeting programs, of the A.A.P.G. can best be described by the use of a homely word that refers to an infestation by certain minute organisms. The abstract appearing at the beginning of this note is in that category. I regret to say that it is not an extreme case. My collection contains several that are worse. Dean Russell of Louisiana State refers to such abstracts as "expanded titles." They could also be looked upon as a table of contents, in paragraph form, with "is discussed" and "is described" added so as to furnish each subject with the verb necessary to complete the sentence. The reader is left completely in the dark not as to what the paper is about but as to what it tells! The information and the interpretation contained therein remain a mystery unless the reader takes the time to read or listen to the entire paper. Such abstracts can be likened to the "teasers" which your local movie manager shows you one week in the hope of bringing you back next week. But the busy geologist is more likely to be vexed than intrigued by the coy abstract.

To many geologists, especially to the tyros in exposition, the writing of the abstract is an unwanted chore required at the last minute by a rule-ridden editor or insisted upon even before the paper has been written by a deadline-bedeviled program chairman. However, in terms of market reached, the abstract is *the most important part of the paper*. For every individual who reads or listens to your entire paper, from ten to five hundred will read the abstract. It is much better to please than to antagonize this great audience. Papers written for oral presentation should be prepared with the deadline the abstract date instead of the delivery date. Later discoveries can be incorporated within the paper—and they would miss the program abstract anyway.

My dictionary describes an abstract as "a summary of a statement, document, speech, etc." and "that which *concentrates in itself the essential qualities of anything more extensive* or more general, or of several things; essence." The definition I like best has been set in italics. May all writers learn the art (it is not easy) of preparing an abstract containing the *essential qualities* of their compositions! With this goal in mind I append an abstract that I believe to be an improvement over the one appearing at the beginning of this discussion.

ABSTRACT

The abstract is of utmost importance, for it is read by 10 to 500 times more people than hear or read the entire article. It should not be a mere recital of the subjects covered, replete with such expressions as "is discussed" and "is described." It should be a condensation and concentration of the *essential qualitities* of the paper.

* Reprinted, with permission of Kenneth K. Landes, from the *Bulletin of the American Association of Petroleum Geologists*, Vol. 35, No. 7, (July, 1951), 1660.

† Editor of the *AAPG Bulletin*, Ann Arbor, Michigan.

PUBLICATIONS RECEIVED

Listed below are all publications received at the business office of the society on subscription and through free exchange for *Geophysics* since publication of the last issue. Periodicals and separates indicated by the asterisk (*) have been forwarded to the Standing Committee on Reviews, and will be placed in the permanent depository of the society at the University of Tulsa Library. These publications are available for loan to members of the society on application to the business manager. Other publications will be held for a short time at the business office. Disposition of books listed is by direction of the Standing Committee on Reviews.

Periodicals

American Journal of Science, Vol. 250, Nos. 3, 4 & 5 (March, April & May, 1952)
**Annales de Geophysique*, Vol. 7, No. 4 (October–December, 1951)
**Annali di Geofisica*, Vol. 4, No. 4 (October, 1951)
**Articles on Geophysics in Current Russian Periodicals*, List No. 34 (March 21, 1952)
**Beitrage zur Geophysik*, Vol. 62, Nos. 1 & 2 (January & February, 1952)
**Boletin de la Asociacion Mexicana de Geologos Petroleros*, Vol. 3, No. 5–6 (May–June, 1951)
**Bulletin of the Hungarian Geological Society*, Vol. 81, No. 10–12 (1951)
**Bulletin of the Seismological Society of America*, Vol. 42, No. 1 (January, 1952)
**Canadian Geophysical Bulletin*, Vol. 4, No. 4 (undated)
**Deutsche Hydrographische Zeitschrift*, Vol. 4, No. 4/5/6 (1951)
Economic Geology, Vol. 47, No. 2 (March–April, 1952)
**Erdmagnetisches Jahrbuch*, No. 4 (1951)
**Erdol und Kohle*, Vol. 5, Nos. 1, 2 & 3 (January, February and March, 1952)
**Geofisica Pura e Applicata*, Vol. 22, No. 1–2 (January–March, 1952)
**Geophysical Notes* (Geophysical Institute, Tokyo University), Vol. 4, Nos. 1 through 8 (1951)
**Glasnik, Matematicko-Fizicki i Astronomski*, Vol. 6, No. 5 (1951)
Journal of Applied Physics, Vol. 23, Nos. 1, 2 & 3 (January, February and March, 1952)
Journal of the Institute of Petroleum, Vol. 38, No. 338 (February, 1952)
**Meteoros*, Vol. 1, No. 4 (December, 1951)
**Nafta*, Vol. 8, Nos. 1, 2, 3 & 4 (January, February, March and April, 1952)
**Nuclear Science Abstracts*, Vol. 5, No. 24 (Dec. 31, 1951); Vol. 6, Nos. 4, 5, 6 & 7 (Feb. 29, Mar. 15, Mar. 31, and April 15, 1952)
**Proceedings of the Cambridge Philosophical Society*, Vol. 48, No. 2 (April, 1952)
The Review of Scientific Instruments, Vol. 23, Nos. 2 & 3 (February and March, 1952)
**Revista Interamericana de Bibliografia*, Vol. 1, No. 3–4 & Index (1951)
**Science*, Vol. 115, Nos. 2983 through 2992 (February 29 through May 2, 1952)
**The Scientific Monthly*, Vol. 74, Nos. 3 & 4 (March and April, 1952)
**Technical Data Digest*, Vol. 17, No. 3 (March, 1952)
**Tellus*, Vol. 3, No. 4 (November, 1951)
**Transactions and Proceedings of the Geological Society of South Africa*, Vol. 54 (151)

Books

American Geological Institute, Report No. 6, *Departments of Geological Science in Educational Institutions of the U.S. and Canada*, Vol. 204 (March, 1952)
Branson and Keller, *Introduction to Geology*, McGraw-Hill, (1952)
Rothe, Edmond and J.-P., *Prospection Geophysique*, Vol. II, Gauthier-Villars, Paris, (1952)

DISCUSSIONS AND COMMUNICATIONS

The Reviews Committee has received "Report for the Year 1950–51" of the Department of Geodesy and Geophysics, University, Downing Place, London. This summary report contains several items which should be brought to the attention of the readers of *Geophysics*, namely:

"*Dynamic Gravimeter*. The development of this instrument has continued throughout the year but a number of difficulties have been experienced which have delayed field trials. Most of these have now been overcome and laboratory tests indicate that measurements, accurate to within a few tenths of a milligal, should be obtainable in a borehole. A further grant has been made by the Paul Instrument Fund for development but not for an assistant. Mr. Gatenby has therefore left the Department and the work is being continued single-handed by Mr. Gilbert."

"*Density Measurements*. An apparatus for measuring the change in volume of rock samples at pressures up to 3,500 kg/cm² has been constructed by Mr. Parasnis. With this he has investigated the consolidation of several different types of clays commonly found in southern England. Most of these obeyed Terzaghi's law up to pressures of about 600 kg/cm² but beyond this some diverged. For globigerina ooze, however, a rather different law of consolidation was obtained."

"*Samples of the Sea Bed*. During the year, two expeditions have been made to collect samples from the floor of the English Channel . . . . The Marine Biological Association . . . again provided the necessary facilities and the Decca Navigator Company kindly lent us one of their instruments . . . (which) proved of great assistance in locating the exact positions from which samples had been taken . . . ."

The remainder of the Report contains discussions of research activities on earth tides, seismology, mass transport by waves, and geomagnetism.

NELSON C. STEENLAND
Chairman of Reviews Committee

CANADIAN SOCIETY OF LOCAL GEOPHYSICISTS

Announcement was made by Dr. Sigmund Hammer, outgoing president, at the Los Angeles Meeting, that the Canadian Society of Exploration Geophysicists has affiliated as a local section of the S.E.G. Officers of the C.S.E.G. are: L. I. Brockway, president; Norman Christie, vice president; William P. Ogilvie, secretary-treasurer; C. H. Moore, district representative. Congratulations to the officers and members of the Canadian Society of Exploration Geophysicists.

ANNUAL SPRING MEETING OF PACIFIC COAST SECTION

The Annual Spring Meeting of the Pacific Coast Section of the Society of Exploration Geophysicists was held at the El Tejon Hotel, Bakersfield, California, on Friday, May 2, 1952.

The program included an afternoon technical session, and, held jointly with the San Joaquin Geological Society, an evening dinner meeting. Both sessions were very well attended.

At the technical session, with Mr. R. B. Galeski, Vice-President, Northern District, Pacific Coast Section, S.E.G., and Program Chairman for the Spring Meeting, presiding, the following papers were given following the theme "Better Utilization and Extension of Geophysical Methods in California."

1. "Remaining Frontiers in the Improvement of Reflection Seismic Prospecting," by R. B. Rice, Phillips Petroleum Co., Bartlesville, Oklahoma. (Read by R. W. Shoemaker, The Ohio Oil Company, Bakersfield, California.)

2. "Limitations of Fault Analysis by the Reflection Seismograph," by Fred Romberg, Geophysical Service, Inc., Dallas, Texas. (Read by Paul Hodge, Geophysical Service, Inc., Bakersfield, California.)

3. "Use of the Averaging Process in Geophysical Procedures," by Dr. C. A. Swartz, United Geophysical Company, Pasadena, California.

4. "The New Profile-Type Dipmeter," by H. B. Hagen, Humble Oil & Refining Co., Houston, Texas.

5. "The Small Operator and the Seismograph," by Drexler Dana, Geophysical Consultant. Bakersfield, California.

Mr. Wallace L. Matjasic, President, Pacific Coast Section, S.E.G., presided at the dinner meeting. Mr. Edward J. Hammer, Pacific Coast Exploration Manager for Humble Oil & Refining Co., addressed the group on "The Role of Geophysics in Future Exploration."

The dates and place of the next Annual Fall Meeting were announced—Thursday and Friday, October 30 and 31, 1952, at the New Statler Hotel, Los Angeles, which will be open by that time. Program chairman for the Fall Meeting will be Mr. David H. Scott, Vice-President, Southern District, Pacific Coast Section, S.E.G.

MAURICE SKLAR, *Secretary-Treasurer*,
Pacific Coast Section, S.E.G.

FIRST ANNUAL MEETING, PERMIAN BASIN GEOPHYSICAL SOCIETY

The first annual meeting of the Permian Basin Geophysical Society, Midland, Texas, convened May 17 at the Scharbauer hotel, Midland, to hear eight technical papers by outstanding earth scientists in morning and afternoon sessions beginning at 9 A.M. About 500 attended.

The following papers were presented. "Geology of the Permian Basin" by Jerald Bartley, consultant, Midland; "Exploration Activity in the Permian Basin" by Leonard Swords, Union Oil Co. of California, Midland; "Isochron Analysis of Seismic Data" by E. D. Alcock, National Geophysical Co., Dallas; "S.S.C. Variable Area Reproducing System" by R. S. Finn, Seismograph Service Corp., Tulsa; "Safety and Geophysical Exploration" by Bart W. Sorge, United Geophysical Co., Pasadena, California; "Elevation Survey by Single Altimeter" by John M. Crawford, Continental Oil Co., Ponca City, Oklahoma; "Remaining Frontiers in the Improvement of Reflection Seismograph Prospecting" by R. B. Rice, Phillips Petroleum Co., Bartlesville, Oklahoma; and "Seismograph Interpretation as Related to Changes in Sedimentary Section in West Texas and New Mexico" by John Daly, Midland.

The Permian Basin Geophysical Society is a local section of the Society of Exploration Geophysicists, with members scattered throughout West Texas and New Mexico. Officers of the section are Lester H. Johnson, president; George A. Grimm, Tide Water Associated Oil Co., first vice president; Paul C. Reed, Forest Oil Corp., second vice president; L. Decker Dawson, Jr., Dawson Exploration Co., Secretary; and R. M. Nugent, Magnolia Petroleum Co., Treasurer. More than 300 earth scientists engaged in exploration for oil in the Permian Basin area belong to the society.

ANNUAL GULF COAST REGIONAL MEETING

The Society of Exploration Geophysicists, Houston section, held its annual Gulf Coast regional meeting May 29–30, 1952, in the Crystal Ballroom of the Rice Hotel, Houston, Texas. Most of the papers presented concerned geophysical problems, but several geological subjects were discussed. The Houston Geological Society, headed by Ralph B. Cantrell, consultant, cooperated with the geophysicists in sponsoring geological papers. Eugene W. Frowe, of Robert H. Ray Co., was in charge of arrangements. Earle W. Johnson, president of General Geophysical Co. is president of the Houston section.

Incoming officers of the Houston S.E.G. section were installed Thursday evening, May 29, at the annual dinner meeting. On Friday evening, May 30, a dance-breakfast was held.

FATHER MACELWANE DISTINGUISHED LECTURER

The North Texas Geophysical Societies (Dallas and Ft. Worth) presented Rev. James Bernard Macelwane, S.J., M.S., Ph.D., as their 1951–1952 distinguished lecturer April 28. Father Macelwane, Dean of the Institute of Technology at St. Louis, spoke on the subject "Microseisms." The meeting was held in the Physics Lecture Hall, Fondern Science Building, at Southern Methodist University in Dallas. Father Macelwane is one of the world's most renowned seismologists and is the author of several books on seismology. He was formerly Assistant Professor of Geology at the University of California in charge of all seismological work there. He is a member of the National Academy of Science, a fellow of the Geological Society of America, a life member and past president of the Seis-

mological Society of America, a fellow of the American Association for the Advancement of Science, serving as Chairman of Section E, Geology and Geography, in 1934, a member of the American Geophysical Union, serving as president of the Section of Seismology 1938–1941, a member of the American Physical Society, the American Meteorological Society, the American Geographical Society, the American Institute of Mining and Metallurgical Engineers and the Society of Exploration Geophysicists.

INAUGURAL MEETING AT THE HAGUE OF THE EUROPEAN ASSOCIATION OF EXPLORATION GEOPHYSICISTS

The inaugural meeting of the newly formed European Association of Exploration Geophysicists was held December 14, 1951 at The Hague.

A Constitution and By-laws were adopted, and the temporary Council was made permanent under chairmanship of A. van Weeldon, B.P.M., The Hague. The E.L.E.G. now has a membership of more than 330 members in Europe, Africa, and the British Isles. Organized originally to become a local section of S.E.G., the Association has been so impressed by the magnitude of the response from geophysicists over such a wide area that it has been decided not to become a local section, but an affiliated society with the S.E.G. The following papers were presented at the first meeting: Opening of meeting and introductory remarks on the use of geophysical exploration in various European countries by Ir. A. van Weelden, B.P.M., The Hague; "Geometrical Construction for the Interpretation of Underground Seismic Records" by Dipl. Ing. Helmut Linsser, Seismos, Hannover, Germany; "The Design of Electromagnetic Geophones" by Dr. A. T. Dennison, Anglo-Iranian Oil Co., Ltd., Newark, Notts., England; "Gravity Effect of Earth Tides" by Dr. B. Baars, B.P.M., The Hague; "Earth Tilts and the Flow of Oil Wells" by Dr. R. K. A. Tomaschek, Anglo-Iranian Oil Co. Ltd., Newark, Notts., England; and "Sur le Calcul de l'Influence Gravimetrique des Structures Defines par les Isobathes, Application a la correction topographique" by V. Baranov, Compagnie Generale de Geophysique," Paris, France.

The second meeting was held in London, May 22 and 23, 1952.

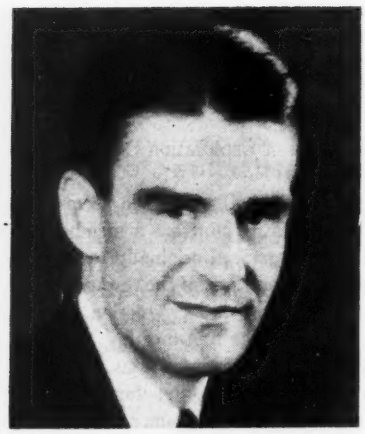
ANNOUNCEMENT

FOREIGN EXCHANGE OF REPRINTS OF GEOPHYSICAL PAPERS

In response to the announcement in January *Geophysics* regarding the exchange of reprints (separates) between authors of geophysical papers in America and abroad, Dr. Hans v. Helms, Geophysicist, Hannover, Germany, Goldener Winkel 4 I, has expressed the desire to cooperate in project. Dr. Helms would be glad to send reprints of his papers to interested persons in the United States.

In the interest of promoting the science of exploration geophysics each issue of *Geophysics* will contain a list of authors who wish to exchange reprints of their papers with those in other countries. All authors desiring to place their names and addresses on this list are requested to notify the business manager of the society.

CONTRIBUTORS



WILLIAM M. BARRET

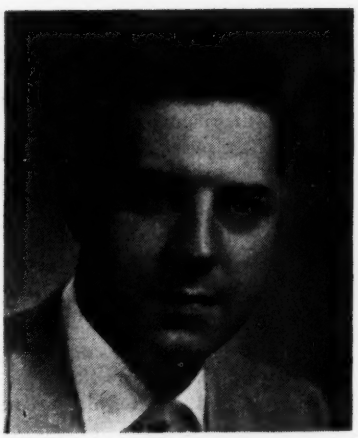
WILLIAM M. BARRET received his academic and pre-engineering training at the University of the South and Columbia University. He was graduated in 1923 from Tulane University with the B.E. degree in Mechanical and Electrical Engineering, and he received his E.E. degree from Tulane in 1932 in recognition of in-absentia research on methods and apparatus for the determination of rock susceptibilities.

Since 1927 he has practiced continuously as a consulting geophysicist, specializing in the magnetic and electrical methods of exploration. He organized the Engineering Research Corporation in 1930 for the purpose of advancing the techniques and apparatus used in magnetic and electrical prospecting, and in 1931 he organized his consulting practice under the firm name of William M. Barret, Inc. He has been President of both companies since their founding.

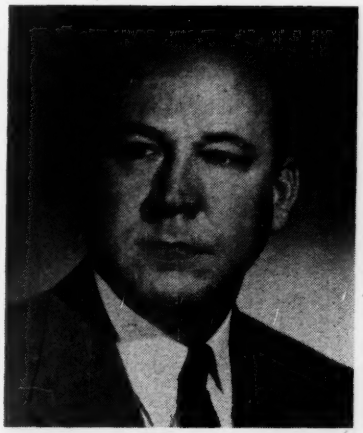
Mr. Barret is the author of numerous bulletins and scientific papers on instrumentation and techniques related to the magnetic and electrical methods of prospecting. For the past 18 years he has devoted much of his time to investigating the application of radio waves to mineral exploration, and he holds some 40 U. S. and foreign patents and pending patents in this field.

He is a member of the Society of Exploration Geophysicists, The American Association of Petroleum Geologists, the American Institute of Mining and Metallurgical Engineers, the American Association for the Advancement of Science, the Louisiana Academy of Sciences, the Ark-La-Tex Geophysical Society, the Shreveport Geological Society, a non-resident member of the Franklin Institute, and a sustaining founder of the American Geological Institute.

ADRIAN A. BECKER received his B.S. degree in petroleum geophysics from St. Louis University in 1949. Upon graduation he was employed by the Geophysical Department of Continental Oil Company. In late 1950, he was transferred to the Development and Research Department where he is working at the present time as Associate Research Geophysicist. He is a member of the Society of Exploration Geophysicists (Associate) and Pi Mu Epsilon.



ADRIAN A. BECKER



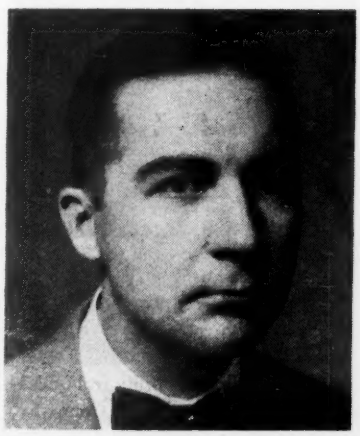
KENNETH E. BURG

KENNETH E. BURG received his B.S. degree in Electrical Engineering from the University of Texas in 1926. Upon graduation he was employed by the Geophysical Research Corporation to do experimental geophysical work. Mr. Burg was computer and observer on one of the original experimental reflection crews and was in charge of several electrical prospecting crews prior to the time he was made party chief on a large refraction crew in 1928.

In 1930 he resigned to join the newly-formed Geophysical Service Inc. As party chief with that organization he worked in the Gulf Coast, Mid-Continent, and Pacific Coast areas, and in Canada. He was placed in charge of the Southern Louisiana and Mississippi areas as district supervisor in 1936, where he was instrumental in developing the techniques and equipment used in that area. In 1941 he was placed in charge of the research department in the Dallas laboratories of Geophysical Service Inc.

Mr. Burg resigned in 1942 to join the Stanolind Oil and Gas Company as seismograph technician. In 1943 he was made head of the seismograph department, and 1944 promoted to geophysical supervisor in charge of all the geophysical operations of the Stanolind Oil and Gas Company. He rejoined Geophysical Service Inc. in January, 1947, as consulting geophysicist, which position he now holds.

Mr. Burg is a member of the Society of Exploration Geophysicists, American Association of Petroleum Geologists, American Geophysical Union, Seismological Society of America, Dallas Geophysical Society, Institute of Radio Engineers, and Tau Beta Pi Honorary Fraternity.

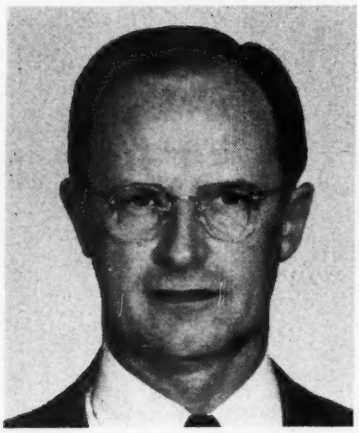


JOHN C. COOK

JOHN C. COOK received the B.S. (honors) in physics at the University of Utah in 1942, the M.S. in physics in 1947 and the Ph.D. in geophysics in 1951 at the Pennsylvania State College.

He served as a member of the radar research staff at the M.I.T. Radiation Laboratory between 1942–45. In 1947 he was assistant recorder for a Texas Company seismic field crew. At Penn. State he held various teachings and research positions in the Physics Department and in the Division of Geophysics and Geochemistry. His duties included research in electric well logging for the Penn Grade Crude Oil Association and extensive field work for the Magnetic and Gravity Survey of Pennsylvania project. He is at present engaged in geophysical research at the Southwest Research Institute, San Antonio.

Dr. Cook is responsible for various publications and a patent dealing with electronics, well logging, and unusual gravitational effects, as well as numerous confidential reports on various subjects. He is an associate member of the Society of Exploration Geophysicists and the American Geophysical Union, a member of Sigma Pi Sigma, and a chapter officer of the Scientific Research Society of America.



H. M. HOUGHTON

H. M. HOUGHTON received the degree of B.S. in electrical engineering from the Massachusetts Institute of Technology in 1927. He was employed by the New York Central Railroad and the Cleveland Union Terminal Co. until March, 1929, at which time he joined Geophysical Research Corp. in Tulsa as office assistant to Dr. B. B. Weatherby.

Mr. Houghton remained with Geophysical Research Corp. as party chief until September, 1943, when he became geophysical supervisor with Tidewater Associated Oil Co., Houston, Texas. He left Houston in March of 1945 to take earthshock measurements on the first atomic bomb at Los Alamos, New Mexico, and later that year be became geo physical supervisor for the Geotechnical Corporation of Canada. While with the latter company he operated in the southwestern part of Alberta, Western Oklahoma, Green River Basin in Wyoming and Utah, as well as the North Flank of the Wichita Mountains in Oklahoma. In December of 1946 he joined Amerada Petroleum Corp., spending somewhat over a year in Oklahoma and going to Alberta as geophysical supervisor in February, 1948.

Mr. Houghton is a member of the Society of Exploration Geophysicists.

F. P. KOKESH was born in Hopkins, Minnesota. He received the degree of B.S. in Electrical Engineering in 1935 from the University of Minnesota, and in 1937 joined Schlumberger Well Surveying Corporation as field engineer. He became party chief and district engineer at Winnfield, La. in 1940. After serving with the United States Army Signal Corps and Air Corps from 1941 to 1945, attaining the rank of Lieutenant Colonel, Mr. Kokesh rejoined Schlumberger. He was district engineer at Monroe, La., and Harvey, La., division engineer of the Mississippi division at Jackson before joining the Schlumberger engineering staff at Houston in 1951.

Mr. Kokesh is a member of Eta Kappa Nu, American Institute of Mining and Metallurgical Engineers, Institute of Radio Engineers, and Society of Exploration Geophysicists Houston Section.

F. P. KOKESH

ADAM B. MALONE received his M.A. degree in Mathematics and Natural Philosophy from Glasgow University in 1936 and joined the Geophysical Department of the Anglo-Iranian Oil Company, Ltd., the following year, serving in Persia. During the war he was attached to the British Admiralty and specialized in magnetic problems.

In 1945, he returned to the A.I.O.C. for whom he has conducted gravity, magnetic and seismic parties in the Bahamas, Papua and Sicily.

Mr. Malone is a member of the Society of Exploration Geophysicsts and of the European Association of Exploration Geophysicists.

HAROLD M. MOONEY

HAROLD M. MOONEY received the degree of B.S. cum laude with major in physics and minor in mathematics, from Harvard College in 1943. He was a student engineer for General Electric Co. until March, 1944, at which time he joined Tennessee Eastman Co. as process engineer, participating in the design and operation of large scale mass spectrographs. From November, 1945 to February, 1946, he served as research chemist for Union Carbide and Carbon Chemical Co. at Oak Ridge, Tennessee. From February, 1946 to September of that year he was field engineer, doing electrical and self-potential exploration in lead and copper districts of Noranda, Quebec, Canada, and Elizabethtown, Illinois for Geophysical Explorations Ltd. In 1948 he received the M.S. degree in geophysics and in 1950 the Ph.D. in geophysics with a minor in physics, both from the California Institute of Technology. Since January, 1950 Dr. Mooney has been assistant professor of geophysics at the University of Minnesota, Minneapolis.

Dr. Mooney is a member of the Seismological Society of America, American Geophysical Union, American Physical Society, and the Society of Exploration Geophysicists.

R. WOODWARD MOORE

R. WOODWARD MOORE was born in Salem, Virginia, on August 9, 1904. He attended the University of Virginia and George Washington University, receiving a B.S. in Civil Engineering from the latter university. In January 1931, after approximately six years experience in highway construction and other engineering fields, he joined the Physical Research Branch of the U. S. Bureau of Public Roads. He has remained with that Federal agency during the past twenty-one years, being closely associated with research on the application of geophysical methods to shallow subsurface explorations since its inception in 1933.

At the present time he is head of the Geophysical Explorations Unit and is engaged in demonstrating the seismic refraction and earth-resistivity methods of test and making field surveys in the several States. He is a member of the American Geophysical Union.

GERALD C. SUMMERS

GERALD C. SUMMERS received the degree of B.S. in electrical engineering from the University of Arkansas in 1942. He has since attended evening graduate classes at the University of Maryland and at Southern Methodist University. From 1942 to 1946 he served as an electronics officer in the U. S. Navy. Following a year of employment in guided missile research at the Naval Research Laboratory, he joined the staff of the Magnolia Petroleum Company Field Research Laboratories in Dallas in 1947. He is today employed at that activity as a senior research engineer in the field of well logging.

Mr. Summers is a member of Tau Beta Pi, the Institute of Radio Engineers, and the Acoustical Society of America.

CHARLES B. VOGEL was graduated from the University of Western Ontario in 1940. He did graduate work at the University of Houston and Wayne University and was an instructor at the Assumption College in the year 1942–43. He was employed as a merchant marine radio operator during 1944 and 1945. In 1945 he joined the staff of the Exploration and Production Research Laboratory of Shell Oil Co., where he has since been engaged in development of acoustical well logging techniques. He is a member of the Society of Exploration Geophysicists, the Acoustical Society of America, and the Institute of Radio Engineers.

CHARLES B. VOGEL

SOCIETY ROUND TABLE

COMMITTEES

Executive Committee, Year Ending in April, 1953

President: Curtis H. Johnson, General Petroleum Corporation, Los Angeles, California
Vice President: Roy L. Lay, The Texas Company, Houston, Texas
Secretary-Treasurer: Carl L. Bryan, Consultant, Shreveport, Louisiana
Editor: Paul L. Lyons, Anchor Petroleum Company, Tulsa, Oklahoma
Past President: Sigmund Hammer, Gulf Research and Development Company, Pittsburgh, Pennsylvania

Standing Committee on Nominations

Chairman: Curtis H. Johnson, General Petroleum Corp., Los Angeles, California
Sigmund Hammer
George E. Wagoner

Standing Committee on Membership

to be appointed

Standing Committee on Honors and Awards

Chairman: (to be appointed)
Sidon Harris ('53)
Norman Ricker ('54)
L. L. Nettleton ('55)
Andrew Gilmour ('56)

Standing Committee on Publications

Chairman: Wm. T. Born, Geophysical Research Corp., Tulsa, Oklahoma
Richard A. Geyer
R. A. Peterson
R. W. Gemmer
Cecil H. Green

Standing Committee on Program and Arrangements

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Sidon Harris
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Reese H. Tucker
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C. M. Moore, Jr.
Ralph B. Ross
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A. van Weelden
Weldon L. Crawford
E. H. Shannon
W. H. Fenwick
Craig Ferris
N. C. Steenland

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Chairman: J. B. Macelwane, S.J., Saint Louis University, St. Louis, Missouri
D. C. Skeels
M. King Hubbert
Beno Gutenberg
C. A. Heiland
Perry Byerly
John C. Hollister

Standing Committee on Distinguished Lectures

Chairman: Milton B. Dobrin

Standing Committee on Radio Facilities

Chairman: R. D. Wyckoff, Gulf Research and Development Co., Pittsburgh, Pennsylvania

Vice Chairman: W. M. Rust, Jr., Humble Oil and Refining Co., Houston, Texas

Bart W. Sorge — V. Robert Kerr — Daniel Silverman
J. P. Woods — Richard Brewer

Standing Committee on Reviews

Chairman: Nelson C. Steenland, Gravity Meter Exploration Co., Houston, Texas

Kenneth L. Cook	Richard A. Geyer	Norman Ricker
Thomas A. Elkins	Lynn G. Howell	Robert J. Watson
Eugene W. Frowe	Robert C. Kendall	Milton B. Dobrin

Standing Committee on Publicity

to be appointed

Standing Committee on Annual Review of Geophysical Activity

Chairman: E. A. Eckhardt, Gulf Research & Development Co., Pittsburgh, Pennsylvania

A. A. Brant — Herbert Hoover, Jr. — D. C. Skeels

Special Committee on Geophysical Case Histories Volume II

to be appointed

Special Committee on Safety

Chairman: Bart W. Sorge, United Geophysical Co., Inc., Pasadena, California

H. M. Thralls — John F. Imle — C. C. Mason

Special Committee on the Microcarding Project

Chairman: Milton B. Dobrin, Magnolia Petroluem Company, Dallas, Texas

Carl L. Bryan — Richard A. Geyer

Directors of the American Geological Institute

L. L. Nettleton (Nov., 1952) — Andrew Gilmour (Nov., 1953)

Representative on Division of Geology and Geography National Research Council

L. L. Nettleton, Gravity Meter Exploration Co., Houston, Texas
(June, 1952)

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee has approved for publication the names of the following candidates for membership in the society. This publication does not constitute an election but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it to the president within thirty days. Names of the references appear in parentheses after the name of each nominee.

ACTIVE

Joseph Franklin Bayhi (S. E. Giulio, R. D. Lynn, J. J. Roark)
David Scott Bays (J. D. Perryman, D. M. Steel, G. E. Seiler)
Geo. Alexander Deabler (R. L. McLaren, Ashton Crain, J. B. Nichols)
William Reginald Hughes (R. M. Bradley, E. J. Gemmill, R. E. Butler)
John Alberg Hugus (L. J. Peters, T. J. O'Donnell, J. C. Heggblom)
Louis Henry Michaelson (R. H. Burton, A. P. Mehringer, F. W. Forward)
Keith Robert Vale (E. J. van der Linden, A. A. Fitch, J. M. Rayner)
Nicolaas van der Sleen (N. B. Sauvé, R. J. Watson, A. B. Bryan)
Randolph Earle Wright (H. E. Itten, H. F. Patterson, P. H. Garrison)

ASSOCIATE

Benson David Blackie (Flint H. Agee, Maurice Sklar, Don C. Short)
Lynn Woodrow Cobena (Roy L. Lay, C. R. Wallace, E. H. Shannon)
John P. Dolan (V. E. Prestine, Dupree McGrady, J. M. Desmond)
John Stanley Hutchison (K. C. Crumrine, R. R. Thompson, R. D. Lynn)
Barry Walter Koch (V. E. Prestine, Dupree McGrady, J. M. Desmond)
Milton Alford McDuff (J. B. Nichols, C. C. Zimmerman, A. B. Hamil)
E. J. Medley (Paul E. Nash, D. R. Dobyns, W. M. Tottenham)
Erwin J. Strecker (W. B. Heroy, Jr., J. W. Horn, J. D. Perryman)
George Byrd Walker (W. B. Heroy, Jr., J. W. Horn, J. D. Perryman)

TRANSFERS TO ACTIVE

George Eldred Conwill (E. F. McMullin, R. C. Dunlap, Jr., M. C. Kelsey)
Dale Edward Fickinger (G. B. Swan, L. E. Whitehead, L. J. Richards)
Robert Dudley Fish (R. G. Elms, Earl Thomas, J. F. Rollins)
Lewis C. Foote (C. H. Green, R. C. Dunlap, Jr., T. P. Ellsworth)
Frederic Carroll Hall (R. N. Bills, P. R. Love, G. M. McGuckin)

TRANSFER TO ASSOCIATE

Marvin Earl Drake (Nils Lago, L. K. Morris, L. O. Bacon)

RESIGNATIONS

Patrick T. Kelly, *Student*
Wylye P. Robertson, Jr., *Associate*
Lucius W. Waterman, *Active*

ADDITIONAL APPLICATIONS APPROVED FOR PUBLICATION

ACTIVE

Lucien Ernest Beaufort (L. Migaux, J. LeBlanc, W. B. Sibley)
LeRoy Samuel Buckie, Jr. (J. B. Macelwane, S.J., H. M. Thralls, J. G. Jackson)
Robert W. Cowden (E. E. Conant, Frank W. Perrin, L. H. Johnson)

Woodrow Wilson Daly (L. F. Guseman, R. W. Upshaw, S. P. Weatherby)
Stephen Winchester Dana (R. A. Peterson, Charles Schwartz, Beno Gutenberg)
Eugene Perry Evans (Jack B. Ferguson, Ray J. St. Germain, E. E. Jones)
Paul Eliot Goodwin (A. W. Black, H. M. Thralls, S. E. Fruehling)
Billy Clifford Johnson (L. F. Uhrig, O. B. Jackson, M. H. McKinsey)
Walter Albert McCabe (D. P. Carlton, H. V. Goss, J. B. Meitzen)
Hilary Igor Ortynski (W. B. Sibley, L. Migaux, J. LeBlanc)
Lilburn B. Ray (E. G. Schempf, V. G. Feather, E. E. Conant)
Arnold Spoor (Leo J. Peters, T. J. O'Donnel, F. O. Mortlock)
Marion Theodore Swanson (J. F. Freel, R. B. Briggs, George P. Montgomery)
James Luther West, Jr. (Karl Dyk, C. J. Long, J. G. Jackson)
William Hatley Young, Jr. (Dean Walling, John A. Adams, O. K. Fuller, Jr.)

ASSOCIATE

Stratton Worth Beesley (T. S. Edrington, L. F. Uhrig, O. B. Jackson)
William Scott Bledsoe, Jr. (J. F. Freel, R. B. Briggs, George P. Montgomery)
William Thomas Brooks (J. M. Desmond, V. E. Prestine, Dupree McGrady)
Kenneth Carl Coulter (C. E. Dalik, W. H. Hohag, Jr., H. J. Kidder)
James Benford Dial (M. C. Kelsey, E. F. McMullin, J. F. Rollins)
Henry Harreld Dinkins, Jr. (Wm. M. Barret, O. S. Petty, Waynard B. Perry)
Herbert Charles Frick (Robert F. Dundon, A. Horton Smith, Robert Dyk)
Walter Frank Gacek (S. G. Pearson, L. I. Brockway, R. J. Copeland)
Glen M. Grosjean (Frank Searcy, J. M. Crawford, D. P. Carlton)
Harvey McClary Haseltine, Jr. (Hugh McCain, Jr., H. D. Marshall, E. C. Livingston)
Gordon Trider Heine (V. E. Prestine, J. M. Desmond, Dupree McGrady)
Wilbur Milton Horn (E. A. Eckhardt, Leo J. Peters, W. B. Robinson)
George Oliver Livo (L. J. Peters, L. W. Gardner, P. Clement)
Jerry Bradford Pennington (Robert F. Dundon, A. Horton Smith, H. B. Peacock)
Donald William Smellie (E. A. Eckhardt, Gary Muffly, E. W. Westrick)
Bryan Francis Smith (Cecil H. Green, Fred J. Agnich, Robert C. Dunlap, Jr.)
Glenn Buddy Taylor (Sam D. Rogers, John Tolk, J. B. Nichols)
Carlyle Grant Thompson (C. M. Moore, Jr., T. A. Halbrook, E. A. Kiesler)
Donald Charles Swanson (H. W. Brown, R. F. Weichert, R. W. Gemmer)

TRANSFERS TO ASSOCIATE

Robert Jay Bean (L. Don Leet, F. Goldstone, W. Hafner)
Harvey Joseph Fitzpatrick (J. J. Pennington, Irvin B. Murray, Jr., H. E. Stommel)
Norbert Clarence Koetting (Julian C. Ashby, James B. Macelwane, S.J., Florence Robertson)
James Robert Moore (Ural Rowe, George B. Somers, Richard Geyer)
Edgar D. Ragan (V. L. Jones, R. F. Weichert, W. C. Merritt)
Donald Raymond Smith (B. G. Swan, Frank L. Searcy, E. L. Mount)

REINSTATEMENT TO ASSOCIATE

D. C. Bowman

RESIGNATIONS

Robert B. Arnold, October applicant, Associate
Bert P. Howerton, Active, Deceased
G. S. Massingill, Student
Joseph A. Sharpe, Active Deceased
Mrs. Francis E. Smith, Associate

MINUTES OF ANNUAL BUSINESS MEETING

LOS ANGELES, CALIFORNIA, MARCH 24, 1952

The Annual Business Meeting of the Society of Exploration Geophysicists was held in Los Angeles California, at the Hotel Biltmore on March 24, 1952. Sigmund Hammer, President of the Society, called the meeting to order at 2:10 P.M.

Minutes of the 1951 Annual Business Meeting were not read since they had been published in *Geophysics*. Reports of the Secretary-Treasurer (R. C. Dunlap, Jr.), and the Editor (Paul L. Lyons) were presented and are attached as Exhibits A and B.

Reports of the following Standing and Special Committees were presented and are attached as exhibits:

Committee	*Chairman*	*Exhibit*
Membership	Francis F. Campbell	C
Geophysical Education	James B. Macelwane, S.J.	*
Public Relations	Charles J. Deegan	D
Radio Facilities	R. D. Wyckoff	E
Honors and Awards	Andrew Gilmour	F
Directors of A.G.I.	L. L. Nettleton	†
Publishing Volume II of Geophysical Case Histories	Henry C. Cortes	‡

Reports of the following Standing and Special Committees were not presented during the meeting, but President Hammer directed they be included as exhibits in the minutes:

Committee	*Chairman*	*Exhibit*
Distinguished Lectures	Herbert Hoover, Jr.	G
Safety	Bart W. Sorge	H
Microcarding Geophysical Literature	M. B. Dobrin	I
Reviews	Nelson C. Steenland	J

The report of the Committee on Geophysical Activity was presented at the morning Technical Session by E. A. Eckhardt, Chairman, and is published in the Technical Section of this issue. Ir. A. van Weelden presented a review of the formation and activities of the European Association of Exploration Geophysicists. The President stated action suggested in the above committee reports would be discussed at the Joint Council Meeting on March 25, 1952.

The President announced the Canadian Geophysical Society is now a Local Section of S.E.G.

The President announced the results of the mail ballot for new officers as follows:

For President:	
Curtis H. Johnson (elected)	628
Gearld H. Westby	579
For Vice President:	
O. C. Clifford, Jr.	539
Roy L. Lay (elected)	660
For Secretary-Treasurer:	
Carl L. Bryan (elected)	785
James L. Morris	401

The meeting adjourned at 3:25 P.M.

R. C. DUNLAP, JR., *Secretary-Treasurer*

* Published in Technical Section of this issue.

† *Geophysics*, Vol. XVII, No. 2 (April, 1952).

‡ *Geophysics*, Vol. XVII, No. 1 (January, 1952).

OFFICERS FOR THE YEAR ENDING IN APRIL, 1953

Left to right: Paul L. Lyons, Editor; Curtis H. Johnson, President; Sigmund Hammer, Past President; Roy L. Lay, Vice President; Carl L. Bryan, Secretary-Treasurer

EXHIBIT A. REPORT OF SECRETARY-TREASURER

The report of the Secretary covers the period from the Joint Council Meeting on April 24, 1951 to March 24, 1952. During this period the Executive Committee met once on November 19, 1951, at Dallas, Texas. All other actions of the Society were covered by thirty-three Executive Orders. Nineteen of these concerned membership applications.

The other fourteen Executive Orders authorized the following action:

May 1, 1951	Salary of Business Manager's assistant increased to $3,000 per year
May 1, 1951	Microcard reproduction of all back numbers of *Geophysics*
May 1, 1951	Flexoprint system purchased for publication of membership list
June 25, 1951	Eastern Regional Meeting in Pittsburgh on October 25, 1951, designated
July 13, 1951	Separate publication of "Index of Wells Shot for Velocity"
July 17, 1951	Donation of SEG publications to Dallas and Shreveport sections
August 28, 1951	Increase of 12.5% in printing rates for *Geophysics*
September 5, 1951	Foreign postage charge eliminated in dues of foreign members
September 30, 1951	Designation of Brookside State Bank as depository for Society funds
October 23, 1951	Expulsion of delinquent members

December 3, 1951	Acceptance of Canadian Society of Exploration Geophysicists as a Local Section
January 19, 1952	Bad debts written off
January 22, 1952	Application for affiliation with A.A.A.S.
February 8, 1952	Salary of Business Manager increased to $5,000.00 per year

The following actions were taken at the Executive Committee Meeting in Dallas on November 19, 1951:

1. Approved appointment of a committee to publish a second volume of *Geophysical Case Histories.*
2. Approved submission to Local Sections of plans for financing distinguished lecture tours.
3. Approved increase from 85 to 120 pages for technical papers published in each issue of *Geophysics.*
4. Authorized employment of an additional assistant for the Business Manager.
5. Approved installation of air-conditioning and heating equipment in the Business Office.
6. Approved recommendations by Mr. C. J. Deegan for reorganization of the Standing Committee on Public Relations.

The Treasurer's report covers the calendar year 1951, and presents an estimate of income and expense for the 1952 calendar year.

The estimates for income and expense are listed in Table I under the 1952 budget and may be compared with the actual figures for 1950 and 1951. The 1952 budget as presented in this report may be modified by action of the Council in its meeting of March 25, 1952.

TABLE I

1950, 1951 OPERATIONS, 1952 BUDGET

	1950	*1951*	*1952 Budget*
Income:			
Membership dues	$12,502.00	$20,668.00	$25,000.00
Geophysics	15,728.82	24,538.88	25,200.00
Geophysical Case Histories	1,518.00	711.05	700.00
Cumulative Index	99.30	77.45	50.00
Safety Posters			200.00
Commissions received	145.90	182.67	200.00
Interest received	125.00	125.00	150.00
Total income	$30,119.02	$46,303.05	$51,500.00
Expenses:			
Operating expenses	$16,304.79	$22,423.05	$26,500.00
Geophysics	14,969.00	15,828.05	19,600.00
Microcards	261.01	634.11	200.00
Total expenses	$31,534.80	$38,885.21	$46,300.00
Net income (loss)	$(1,415.78)	$ 7,417.84	$ 5,200.00

The Society's improved financial position from 1950 to 1951, while striking, was anticipated in the Treasurer's Report of a year ago. The figures in Table I clearly show increased income from dues and *Geophysics* is responsible for this change.

The balance sheet for December 31, 1951 shows the Society to be in a very strong cash position. Reserves appear to be adequate and no difficulty is anticipated in financing the publication of the second volume of *Geophysical Case Histories*. If the incoming officers and Council agree the Society's present reserves are adequate, it is recommended future operating profits be used to benefit directly the membership of the society.

R. C. DUNLAP, JR., *Secretary-Treasurer*

The report of the independent auditors for the year 1951 follows:

BROWN & BALA
Certified Public Accountants
1110 Hunt Building
Tulsa 3, Oklahoma
January 17, 1952

To the Executive Committee,
Society of Exploration Geophysicists,
Tulsa, Oklahoma.

We have examined the balance sheet of the Society of Exploration Geophysicists as at December 31, 1951 and the related statement of net profit for the year then ended. Our examination was made in accordance with generally accepted auditing standards, and accordingly included such tests of the accounting records and such other auditing procedures as we considered necessary in the circumstances except that, as instructed, we did not apply the customary procedure of confirming receivables by direct communication with debtors and the United States Savings Bonds in the hands of the Secretary-Treasurer in Dallas, Texas were not inspected by us but we secured an affidavit from the Secretary-Treasurer as to the bonds in his possession.

The system of internal control of disbursements is excellent, however the office staff is too small to permit the establishing of an effective system of internal control of receipts and we therefore extended our tests of the transactions beyond those necessary where an adequate system is in force. We compared the recorded cash receipts in totals with deposits shown on the bank statements for the year and examined paid checks, cash vouchers, and other data in support of transactions as well as executive orders and council proceedings.

In our opinion, subject to the foregoing comments relating to receivables, bonds and to the system of internal control, the accompanying balance sheet and related statement of net profit present fairly the position of the society as at December 31, 1951 and the results of its operations for the year, in accordance with generally accepted principles of accounting applied on a basis consistent with that of the preceding year.

BROWN & BALA

SOCIETY OF EXPLORATION GEOPHYSICISTS

BALANCE SHEET—DECEMBER 31, 1951

ASSETS

Cash		$24,212.68
Accounts receivable:		
Membership dues	$ 1,319.15	
Other	2,313.64	
	$ 3,632.79	
Less—Allowance for bad debts	700.00	2,932.79
Inventory of publications (see note)		257.91
Investment in United States Savings Bonds, at cost		13,880.00
Office equipment	$ 3,670.06	
Less—Accumulated depreciation	980.62	2,689.44
Deferred expenses:		
Agency commissions and library discounts		356,93
		$44,329.75

LIABILITIES

Accounts payable		$ 1,353.79
Deferred income:		
Membership dues—1952	$15,273.17	
Subscriptions to and advertising in *Geophysics*	2,843.38	18,116.55
Surplus:		
Balance, December 31, 1950	$17,441.57	
Net profit for the year, per accompanying statement (Exhibit "B")	7,417.84	24,859.41
		$44,329.75

Note—

The accounts do not reflect the inventory of back numbers, reprints, and microcards of *Geophysics*, the cost of which was charged off at time of original publication, or the inventory of special publications of prior years. Proceeds of sales of special publications are applied against their cost until cost is absorbed; any balance of cost is reduced to a maximum of one-half the cost of unsold copies at the end of the year of publication and is written off at the end of the subsequent year. There were no special publications in 1951. The Executive Committee through executive order number 274 dated July 13, 1951 authorized the printing of a well index at an estimated cost of $1,239.91. $257.91 was expended during 1951 on this project.

SOCIETY OF EXPLORATION GEOPHYSICISTS

STATEMENT OF NET PROFIT

FOR THE YEAR ENDED DECEMBER 31, 1951

Income:			
Membership dues		$20,668.00	
Publications—			
Advertising	$15,955.84		
Subscriptions	6,158.85		
Back numbers	1,737.55		
Microcards of back numbers	63.75		
Reprints	821.96		
Geophysical Case Histories, Vol. I	711.05		
Cumulative Index of *Geophysics*	77.45		
Safety posters	97.30		
Discounts allowed	(647.17)	24,976.58	
Commissions on sales of books published by others		182.67	
Interest received		125.00	
Miscellaneous		350.80	$46,303.05
Expenses and publication costs:			
Salaries—			
Business manager		$ 4,500.00	
Office assistant		2,900.00	
Commissions—			
Advertising—business manager		3,433.06	
Advertising—agencies		2,093.89	
Subscriptions—agencies		487.70	
Office rent		600.00	
Utilities		174.66	
Postage		1,325.31	
Stationery and office supplies		2,412.26	
Telephone and telegraph		362.22	
Auditing		428.80	
Depreciation of office equipment		295.43	
Advertising		108.58	
Provision for bad debts		829.06	
Federal insurance contributions tax		111.82	
Annual meeting expense		33.98	
Regional meeting expense		283.82	
Contributions		1,000.00	
Traveling expense		16.70	
Miscellaneous expense		1,025.76	
		$22,423.05	
Publication costs		16,462.16	38,885.21
Net profit			$ 7,417.84

EXHIBIT B. REPORT OF THE EDITOR

1951–1952

This report covers the period April 1, 1951 through March 23, 1952, representing the first year of the present Editor's term of office.

Thirty-seven technical papers, totalling 486 pages, were printed in the four issues of *Geophysics* published during this period. In addition, 41 Reviews totalling 38 pages and 23 pages of Patents make a grand total of 547 pages of technical material printed; this is an average of 137 pages of technical material per issue.

Geophysics has more than doubled in size in the period 1936 through 1951, representing 16 volumes. A great amount of this growth has resulted from increased advertising and non-technical material published. Technical material published increased about 50 percent from an early average of 85 pages per issue to 130 in 1951.

Yet the membership of the Society has increased six-fold in that interval, and it is apparent that an increase in the number of papers printed is warranted by the greater membership of the Society.

A nominal limit of 85 pages of technical material has been given the Editor. The Council of the Society approved an increase to 130 pages at the Dallas meeting November 19, 1951.

The Editor has pursued a policy of solicitation of papers to achieve the goal of an increased journal containing a wide variety of pertinent technical material, including mining geophysics and contributions from outside the United States. A large backlog of manuscripts is now on hand, and it is possible that the availability of excellent material may warrant an even larger issue, providing increased funds are available.

All authors who present papers at regional, sectional, and national meetings are repeatedly solicited, and new members of the Society are solicited if their experience indicates a worthy paper may be forthcoming.

The Editor notes with some alarm, however, the sizeable increase in length of manuscripts submitted. The overall average size of a printed paper has been 12 pages in the past. In fairness to authors, it has been necessary to require reasonable limitation of long manuscripts to a moderate number of pages.

A new section of Nomograms has been instituted and is scheduled to start in the April 1952 issue.

The Editor wishes to express his sincere appreciation to Mr. O. F. Ritzman for continuing his time-consuming and accurate Patents section.

Particular thanks are due to Nelson C. Steenland and the twelve members of the Reviews Committee for an outstanding service in bringing the attention of the profession to the diversified literature of geophysics.

The Editor is indebted to Sigmund Hammer, president of the Society, for his interest in *Geophysics* and his aid in the solicitation of manuscripts.

The Editor is also greatly indebted to the Standing Committee on Publications, of which W. T. Born is Chairman, for able assistance in solving the various problems involved in publishing *Geophysics*, to the many anonymous referees who have freely contributed considerable effort in refereeing manuscripts, and to Mr. Colin C. Campbell, business manager, for his cooperative editorship, since he edits the non-technical and advertising sections which now occupy over half the pages of the journal.

Respectfully submitted,
PAUL L. LYONS, *Editor*

EXHIBIT C. REPORT OF THE STANDING COMMITTEE ON MEMBERSHIP

1951–1952

The report of the Membership Committee consists of two tables to show the changes in numbers of members and of a review of recruiting practices. The report concludes with three recommendations for action by the incoming officers and council.

Table I shows the number of honorary, active, associate, and student members at the end of the last four calendar years and the changes during 1951. The Society reached a new high in total membership in each year, and stood at 2,836 at the end of 1951. The only class of membership to decline in 1951 was the student category which lost 22.

Table II shows the changes in membership during 1951 in more detail. There were 194 active members elected in 1951 and of these 69 or 36% were transfers from associate membership. Of the 246 new associate members 79 or 32% came from the ranks of student members. There were 71 new student members elected in 1951 compared to 66 in 1950, which is a figure not given in the table. The reports of the committee on geophysical education by Father James B. Macelwane show there were 940 undergraduate and graduate students in geophysics in 1949–50 compared to 864 in the same institutions in 1950–51. Hence the 8% loss in student membership in S.E.G. may be closely related to the 8% decline in number of students. However the total number of students in all institutions reporting to Father Macelwane is more than 1,400, so less than 20% of them are members of the S.E.G. There are concentrations of students in Houston, Fort Worth, and Los Angeles where student sections might be organized.

Analysis of the records of the 93 members who left the Society in 1951 shows that only 53 gave a specific reason. Two objected to the increase in dues; 28 became delinquent in dues payments and probably were dropped for the same reason. Fourteen members changed occupations and seven entered military service. There were two changes in the official membership roll due to death. The passing of George W. Carr and Eric U. Garpner is noted with regret.

In August 1951 the Business Manager sent out application forms to every member with a request to place them in the hands of a fellow employee or friend who might be interested in membership. Application forms were sent to non-members who attended the Pittsburgh and Dallas regional meetings in 1951. These recruiting methods were recommended in the report of the Membership Committee for 1950. They will be continued. In the fall of 1949 the Business Manager canvassed the rolls of local sections for qualified candidates for the national society. This recruiting method should be tried again in 1952.

One local section reported a spectacular growth in membership. Inquiry revealed that dynamite salesmen had been enlisted as recruiting agents. The officers of the section advise against other sections using this method.

In the opinion of the committee the best incentive for recruiting members is the high quality of the papers printed in *Geophysics*. This depends in turn upon the quality of the papers presented orally at local, regional, and national meetings, and upon the efforts of district representatives, program chairmen, and the editor to secure the best of them for *Geophysics*. The committee believes that the primary responsibility for the preparation of papers should remain with the local sections. Still local sections might use a speaker from another section once or twice a year to advantage. The larger local sections have done this often in the past, but there have been instances where a potential speaker from one section made a trip to the vicinity of a distant local section without the program chairman of that section knowing of the trip. A committee with individual members in Tulsa, Dallas, Houston, and possibly Los Angeles, could keep posted on the program schedules of all the local sections and on the itineraries of men who can speak to local sections in the course of business trips. With this information a committee member would be able to advise the program chairman of a distant local section about the impending visit of a qualified speaker in time to fill an open date or in time to plan a special meeting.

In conclusion the Membership Committee recommends that:

1. Student sections should be encouraged in Houston, Fort Worth, and Los Angeles.
2. The rolls of local sections should be canvassed for candidates for membership in the national society.
3. A committee should be organized to facilitate the exchange of speakers between local sections.

Respectfully submitted,
FRANCIS F. CAMPBELL

TABLE I

S.E.G. MEMBERSHIP 1948–1951

	1948	*1949*	*1950*	*1951*	*Change in 1951*
Honorary	3	3	4	4	0
Active	1,446	1,597	1,674	1,829	155
Associate	271	494	603	740	137
Student	102	245	285	263	− 22
Total	1,822	2,339	2,566	2,836	270
Increase over preceding year	229	517	227	270	

TABLE II

CHANGES IN S.E.G. MEMBERSHIP—1951

	Honorary	*Active*	*Associate*	*Student*	*Total*
December 31, 1950	4	1,674	603	285	2,566
Elected	0	194	246	71	511
Dropped	0	− 39	− 40	− 14	− 93
Transferred to higher grade	0	0	− 69	− 79	−148
December 31, 1951	4	1,829	740	263	2,836

EXHIBIT D. REPORT OF THE STANDING COMMITTEE ON PUBLIC RELATIONS

1951–1952

Events of the past year indicate clearly that this committee has a big job to do in educating the rank and file of our members and the officers of some local societies. All of our national officers are far ahead of the rest of the society in understanding and appreciating the value of public relations.

I have a lengthy letter from Mr. Curtis Johnson, which I intend to submit to my committee, almost in toto, as an ideal long range objective for this committee's work.

A short, practical Public Relations Manual was prepared and sent to all local society Presidents and Associate Members of the Committee during the year.

In view of the late start, and the delays in securing an organization for this year, I recommend that all present committee members, except the Chairman, be reappointed for another year.

If the incoming President and Executive Committee wish to appoint me Chairman for one more year, I will serve. But if they do, I will endeavor to find a successor among my committee members. As a member of a consulting firm with only a small staff, I have found it difficult to devote enough time to this job to do justice to the S.E.G. and also to my associates in the firm. If the incoming officers wish to appoint someone else, it might be better for S.E.G., and personally I will be happy to help him in any way at all times.

In addition to the splendid cooperation from all national officers, I would like to recognize especially the able, timely and wholehearted work of Mr. Colin C. Campbell, Business Manager, in all matters touching the Public Relations activities of our Society.

Respectfully submitted,
CHARLES J. DEEGAN
Chairman, Public Relations Committee

EXHIBIT E. REPORT OF THE STANDING COMMITTEE ON RADIO FACILITIES

1951–1952

The organization and membership of this Committee has not changed since the last report which included a comprehensive list of the Regional Subcommittees. It also included an outline of our affiliations with the American Petroleum Institute Central Committee on Radio Facilities and the National Petroleum Radio Frequency Coordinating Association.

(1) *Radiolocation Service*

The major problem of our agenda at the beginning of the year was the General Radiolocation Hearing, FCC Docket 9233, held June 4–5, 1951, at which the Chairman of the Commission, Wayne Coy, presided.

Your committee was represented at the Hearing by Messrs. Wyckoff and Rust through the API Committee and Special Representative Joseph E. Keller. In addition to general testimony and exhibits presented by them, representatives of Hastings Instrument Company on the Raydist System and Seismograph Service Corporation on Lorac presented testimony specific to phase-comparison systems. Support was also given to our case by the Department of the Interior and the Coast and Geodetic Survey who are using these methods.

At the request of Commissioner Coy, a third day was spent in conference with FCC personnel to aid in outlining means whereby the Radiolocation and Disaster Services might share the 1,750–1,800 kc channels without risk to the latter.

As a result of this Hearing, on December 19, 1951, FCC released a Report and Order (FCC 51-1235; 70224) effective February 1, 1952, and providing for an Industrial Radiolocation Service on a developmental basis. Licenses for such Radiopositioning Stations will be for a term of two years or until July 1, 1955, whichever date is earlier.

Frequencies Available

(a) 1,750–18,00 kc—Available only for petroleum industry service within 150 miles of the shoreline of the Gulf of Mexico. Restricted to 500 watts and a 3 kc bandwidth unless adequate showing is made for greater bandwidth. Requires special liaison with the Disaster Service to assure against interference.

(b) 2,450–2,500 mc—Land and Mobile Radiopositioning Stations and Speed-measuring devices.

(c)

2,900–3,246 mc	5,460–5,650 mc
3,266–3,300 mc	9,000–9,300 mc
5,250–5,440 mc	9,320–9,500 mc

For Land and Mobile Radiopositioning Stations

(d) Special authorization may be obtainable on Federal Government frequencies where the permission of the appropriate Government agency can be obtained on the basis that such assignment is necessary or required for coordination with Government activities.

(2) *Definition of Geophysical Operations*

A mail vote was submitted to the SEG membership at the request of the NPRFCA and API Committee for the purpose of clarifying the following basic questions pertinent to recommendations for geophysical frequencies by NPRFCA regional coordinators.

Based on the response from 37 operators in the industry the following instructions were submitted to the NPRFCA through the API Committee.

Frequency coordinators' recommendations for geophysical frequencies within the Petroleum Service should include:

(a) Temporary base-to-mobile stations for coredrill or so-called geological structure-drill exploratory operations.

Such authorization is not to extend to the operator the use of these channels for coordination of shothole or other operations outside the structure-drill category. The NPRFCA recom-

mendation is to include a clause specifically limiting geophysical channels to coredrill operations for the purpose of delineating shallow structures in the commonly accepted meaning of the term.

(Vote—35 to 1)

(b) For temporary base-to-mobile communications such as isolated camps, coordination of radiolocation networks, etc., requiring relatively long range, the coordinators should recommend the use, if at all possible, of the 2,292 kc, or preferably, the 4,637.5 kc channels.

(Vote—32 to 5)

(c) Slim-hole or other exploratory drilling operating have producing horizons as objectives are not to receive recommendations for the use of Petroleum Service channels reserved exclusively for geophysical use under NPRFCA agreements.

(Vote—37 to 0)

(3) *Recommendations*

(a) The present organization within the Petroleum Radio Service, comprising the National Petroleum Radio Frequency Coordinating Association, the API Central Committee on Radio Facilities, and its several Subcommittees representing various phases of the Service including Geophysics, is functioning smoothly and effectively and with the full cooperation of the Federal Communications Commission. Through the API Committee and Washington representative Mr. Joseph Keller, we have the necessary headquarters facilities with legal and administrative advice to affect prompt and efficient action when required. The financial support of this necessary headquarters setup by operators in the Geophysical Service as requested annually by the API should receive prompt attention.

(b) Your Radio Facilities Committee has disposed of all current matters on its docket. However, since the proper functioning of this Standing Committee requires the existence of the Regional Subcommittees, they should be intact even though no definite activity is pending.

R. D. WYCKOFF, *Chairman*
W. M. RUST, JR., *Vice Chairman*

Members—Regional Chairmen
California—Bart W. Sorge
Dallas, Texas—E. M. Shook
Ft. Worth, Texas—V. R. Kerr
Houston, Texas—W. M. Rust, Jr.
Shreveport, La.—Richard Brewer
Tulsa, Oklahoma—Daniel Silverman

EXHIBIT F. REPORT OF THE STANDING COMMITTEE ON HONORS AND AWARDS

1951–1952

The members serving on the Honors and Awards Committee during the past year were Frank Goldstone (1952), Sidon Harris (1953), Norman Ricker (1954), L. L. Nettleton (1955), and Andrew Gilmour (Chairman).

Some thirteen papers were mentioned by the members of the Committee for consideration for the Society's Best Paper Award. Dr. L. Y. Faust's paper, "Seismic Velocity as a Function of Depth and Geologic Time," was recommended for this honor on the first ballot.

The Committee recommended Dr. E. A. Eckhardt for Honorary Membership of the Society in recognition of his outstanding record and stature as a geophysicist and his continued work for and interest in the Society.

These awards were made at the joint session.

The Committee is struggling with the selection of a crest for the Society. Fifty-five designs have been submitted. Entries closed March 1st. According to the rules of the contest a Life Membership will be given to the member whose design is adjudged as best by the Honors and Awards Committee.

ANDREW GILMOUR, *Chairman*

EXHIBIT G. REPORT OF THE STANDING COMMITTEE ON DISTINGUISHED LECTURES

1951–1952

First, let me say that I have very grave doubts that the program is a practical one for the S.E.G. Our membership is predominantly a younger one, and they are still active in their business and professional careers. We do not have a large group of older, independent and well-known members of recognized accomplishment to draw upon from within our own group, as does, for instance, the A.A.P.G.

One has only to try to round up speakers, as I have, who will agree to make a hard two-weeks trip involving frequent one-night stands to appreciate that few of our members can get away for the length of time required. We have specifically eliminated candidates who would turn it into a personal selling tour for their gadgets or contract organizations. Those who might be acceptable usually decline because of the obvious pressure of work. I am referring, here, to our own active membership, and automatically excluding National officers of the Society, because they make it a point to appear before the various Sections at their regular meetings as often as possible as one of the responsibilities of their positions.

Acceptable outside talent, not connected with the Society, are even more difficult to locate. Frankly, the S.E.G. does not mean enough to any that I have contacted, to cause them to make the sacrifice. Perhaps if times were a little harder it could be accomplished more easily, but this is obviously not a propitious point in the business cycle to bring about that urge.

There are undoubtedly a number of alternatives of the Distinguished Lecturer Program. It is my own feeling that the various Sections could accomplish their desired end of getting an interesting speaker from outside their local membership, by exchanging visits from the officers or members of other Sections. These would not involve prolonged tours, which constitutes one of the major stumbling blocks to the Distinguished Lecturers Program as at present envisaged. Each Section should arrange for its own speakers, from other areas where there will undoubtedly be problems of a similar nature. In many instances business trips can be arranged in advance to coincide with Section meetings with little, if any, attendant expense to the Society. If a clearing house for such speaker-exchange is desired, it should be set up either at the Annual Convention under the auspices of the Society, or by the permanent staff at Society Headquarters. Each interested Section should have one member of their Program Committee assigned to handle that matter exclusively. It should not be done by appointing a general committee, such as the present Distinguished Lecturers Committee, who are widely scattered and in many cases are not actively in touch with local Sections.

To sum up this part of my comments: It seems to me we should start something of our own, suitable to our own needs and resources, and not try to copy the A.A.P.G. A program best suited for them may not necessarily fit our own capabilities.

It may well be that the Society will wish to continue with the present Distinguished Lecturer Program, not withstanding the difficulties I have pointed out. In that event, the following suggestions may prove helpful.

The Chairman should be someone in the central part of the country, preferably close to Society Headquarters, as he will need the close cooperation of the paid staff. It would be best if he was a member of an educational institution, with a good deal of time to devote to the job. He should be in contact with as many people as possible, both professional and academic, for the job itself is to run a full fledged Speakers Bureau—getting lecturers, determining the subject matter, arranging reservations, re-arranging the dates of Section meetings, handling financial details and carrying on a voluminous correspondence with the various program chairmen.

A committee is not of much help unless the members reside in close proximity to the chairman. It is essentially a one-man job.

In closing, I would again like to stress that I think the idea of a Distinguished Lecturers Program is an excellent one, but that practical problems make it extraordinarily difficult, if not impossible, to carry out.

HERBERT HOOVER, JR.

EXHIBIT H. REPORT OF THE SPECIAL COMMITTEE ON SAFETY

1951–1952

The Special Committee was appointed by the President upon approval by the Society's Council at its session in St. Louis—April 1951. The members of the Committee are:

Robert S. Duty, Jr.
Humble Oil and Refining Company, Houston, Texas
John Imle
Geophysical Service, Inc., Dallas, Texas
John A. Legge, Jr.
215-A Eighth Avenue East, Calgary, Alberta, Canada
Bart W. Sorge (Chairman)
United Geophysical Company, Pasadena, California
H. M. Thralls
Seismograph Service Corp., Tulsa, Oklahoma

During the year the Committee has been gathering a mailing list of all companies and individuals engaged in the geophysical business who are interested in safety. We have also collected pertinent safety posters which are particularly applicable to geophysical operations. In conjunction with the Tulsa business office of the Society, these posters have been made available to the industry on a non-profit basis. During the four months' period that these posters have been available, over eight thousand of them have been sold.

The Committee has cooperated with the Bureau of Mines, the American Petroleum Institute, and the National Safety Council in an endeavor to secure for these organizations more complete statistical accident information from our industry. Indications at the time of the writing of this report are that our efforts have resulted in a substantial increase in the amount of information gathered. When this information is compiled and made available, it should prove a valuable yardstick by which our industry's activities, safetywise, can be judged.

Discussions on safety problems were sponsored during the year at regional meetings. In connection with the national meeting in Los Angeles, the Committee has arranged an interesting program.

A year ago the members of this Committee, as individuals, established a Geophysical Accident Information Exchange, which has grown from the original number of five to twenty-one participants. This Information Exchange is carried on through an agent, an office service organization in Tulsa which has no connection with the oil industry. All information is sent in by the participants, and all traces of company identification are removed. The reports are mimeographed, and the collected information returned to each participant. This arrangement has proven very valuable to the companies participating. It has been an aid in helping them plan their own accident prevention programs. A summary of the results of this Accident Information Exchange will be presented at the safety session by Mr. H. M. Thralls.

In line with instructions received from the Council a year ago, the Committee has been extremely cautious in undertaking action which might present legal complications. This policy caused a delay in the examination by the Committee of a Code of Operating Procedures submitted to it by a government agency before these rules and regulations were put into effect. The members of the Committee, as individuals, finally offered to review the proposed Code, but at the writing of this report it appears that the Code has been put into effect and will now have to be observed by all geophysical parties working in the area. In order to avoid this difficulty in the future, the Committee has suggested to the Executive Committee of the Society, that legal counsel be secured to clarify the scope of action, in the interest of safety and accident prevention, that this Committee might undertake without incurring any liability on the part of the Society.

This Committee has found that there is a real need for someone to further the interests of safety and accident prevention in our industry. As a result, it is our recommendation that this Committee be continued for another year.

Respectfully submitted,

BART W. SORGE, *Chairman*

EXHIBIT I. REPORT OF THE SPECIAL COMMITTEE ON MICROCARDING OF GEOPHYSICAL LITERATURE

1951–1952

The Committee on Microcarding of Geophysical Literature, consisting of R. A. Geyer, Carl Bryan, and M. B. Dobrin, Chairman, gave an interim report last November at the Dallas Regional Meeting. This report was published in the January 1952 issue of *Geophysics*. At that time, the Society was about to send out an inquiry to 130 libraries to ascertain whether there was sufficient demand for complete back files of geophysical journals to make the reproduction of the material on Microcards economically feasible. The Microcard Foundation had advised us that it would require a guarantee of ten sales for each set of cards before it could undertake to publish the back files of any journal in this form.

The returns on our questionnaire have been most encouraging. Of the forty-six replies we have received, thirty-nine indicated an interest in purchasing one or more of the twelve journals we were proposing. Twenty-two of these thirty-nine replies were from university libraries, twelve from libraries of oil companies or geophysical companies, one from a public library, and four from miscellaneous sources. Although we did not ask for actual commitments, we did request that the prospective purchasers check the items they would "probably" buy in one column and those they would "possibly" but in another.

Seven companies replied that they would "probably" purchase a complete set of all twelve journal files. No journal had less than twelve "probable" purchasers or less than five "possible" ones. One journal had eighteen "probables" and five "possibles" for a total of twenty-three. The smallest total was eighteen. A tabulation of the replies by journal and by institution or company is attached for the record.

In view of the excellent response to our questionnaire, the Committee believes that there is no question that at least ten sets of each of the twelve journals can be sold within a short time. It is

TABULATION OF REPLIES BY JOURNAL

As of March 10, 1952

Journal	Would *Probably* Purchase Complete Set if Issued on Microcards (A)	Would *Possibly* Purchase Complete Set if Issued on Microcards (B)
1. Zeitschrift fur Geophysik	18	5
2. Monthly Notices of The Royal Astronomical Society, Geophysical Supplement	12	7
3. Bulletin of the Earthquake Research Institute, Tokyo (in English)	13	6
4. Beitrage zur Angewandten Geophysik	18	5
5. Terrestrial Magnetism and Electricity	13	6
6. Japanese Journal of Astronomy and Geophysics	15	7
7. Gerlands Beitrage zur Geophysik	15	8
8. Geophysical Magazine, Tokyo	14	7
9. Annali di Geofisica	14	7
10. Annales de Geophysique	15	6
11. Geofisica Pure e Applicata	12	7
12. Transactions, American Geophysical Union	12	7

ANALYSIS
of
REPLIES TO QUESTIONNAIRE ON MICROCARDS

Tabulation of Replies by Institution

	No. of sets that would *Probably* be Purchased	No. of sets that would *Possibly* be Purchased
A. *University Libraries:*		
1. California Institute of Technology		3
2. Seismological Laboratory, Cal. Tech.	1	
3. Colorado School of Mines Library	7	5
4. Florida State University		6
5. Lehigh University	7	3
6. Massachusetts Institute of Technology	4	
7. Missouri School of Mines & Metallurgy		5
8. Northwestern University	3	1
9. Mineral Industries Library, Penn State College	4	
10. University of Kansas		4
11. University of Michigan, General Library		2
12. University of Nebraska, General Libraries		3
13. University of Pittsburgh	2	
14. University of Rochester	4	
15. Iowa State College	2	
16. University of North Carolina	11	
17. University of Southern California		9
18. University of Oklahoma	2	4
19. Harvard College Library	1	
20. University of California at Los Angeles	6	
21. University of Florida		1
22. University of Oregon		1
B. *Commercial Libraries:*		
1. The Atlantic Refining Co.	12	
2. The Carter Oil Company, Research Dept.		4
3. Continental Oil Company	7	4
4. Geophysical Research Corp.	12	
5. Gulf Research & Development Co.		5
6. Humble Oil & Refining Co.	6	6
7. Magnolia Petroleum Co., Field Research Labs.	12	
8. Seismograph Service Corp.	6	
9. The Texas Company	12	
10. United Geophysical Co.	12	
11. California Research Corp.	1	4
12. Texas Instruments Inc.	12	
C. *Public Library:*		
1. Oklahoma City Library		1
D. *Miscellaneous:*		
1. Southwest Research Institute	8	
2. Dr. John C. Cook	1	3
3. J. T. Wilson, University of Michigan	3	
4. Dallas Geophysical Society	12	

felt that the Society would be incurring virtually no risk of financial loss in guaranteeing the sale of ten sets to the Microcard Foundation.

We therefore recommend that the Executive Committee authorize the Society to purchase from the Microcard Foundation, for subsequent resale, ten sets of Microcards of each journal listed in the attached table less the number, up to ten, that the Foundation has sold in the first three months after it has received its invoice from its manufacturer. The maximum possible cost to the Society would be approximately $4,500 in the case that the Foundation can sell none at all, an extremely improbable occurrence in view of the considerable demand we have demonstrated. If a few sets would have to be bought on the basis of this agreement, the Society should have no difficulty in selling them within a reasonable time and thus recovering its expenditure.

It is also suggested that the Society consider the purchase of one complete set of all the microcards for its repository at the University of Tulsa, cards from this set to be available for loan to members of the Society. This would cost the Society only $450 and would constitute a distinct service to members located where they do not have access to the university or company libraries holding this literature.

MILTON B. DOBRIN, *Chairman*

EXHIBIT J. REPORT OF THE STANDING COMMITTEE ON REVIEWS

1951–1952

The Reviews Committee appointed in 1951 by the Executive Committee completed three-fourths of its first year of service with the January, 1952, issue of *Geophysics*. The membership, in addition to the Chairman, has been as follows: K. L. Cook, M. B. Dobrin, T. A. Elkins, E. W. Frowe, R. A. Geyer, L. G. Howell, D. S. Hughes, R. C. Kendall, N. Ricker, R. A. Stehr, I. Tolstoy, and R. J. Watson. Reviews have also been written by J. E. White, R. A. Simon, C. W. Horton, W. J. Yost, A. J. Hermont, J. L. Worzel, R. W. Garwick, L. L. Nettleton, H. G. Farmer, Jr., and the committee sincerely appreciates the efforts of these outside contributors.

Thirty-one reviews have appeared; seventeen of books and fourteen of articles. It is the aim of the committee to increase the number of interesting reviews but only insofar as the amount of worthwhile, new publications permit.

The Chairman is pleased to be able to express his appreciation to the committee, to Colin Campbell, and to the publishers, all of whom contribute so vitally to this work.

N. C. STEENLAND

PAPERS PRESENTED AT THE TWENTY-THIRD ANNUAL MEETING BILTMORE HOTEL, LOS ANGELES, CALIFORNIA

MARCH 23–27, 1952

Discovery of the Durham Gas Field, Butte County, California.

L. F. MALARIN, Standard Oil Company of California, Bakersfield, Calif.

The history of the discovery of the Durham Gas Field is described from both the geological and geophysical standpoint. Structure of the field as determined from seismograph data and as verified by subsequent drilling is shown.

The Geophysical Discovery and Development of the Bayou Couba Dome.

LOUIS F. MELCHOIR, Gulf Research and Development Company, Pittsburgh, Pennsylvania.

This case history of the Bayou Couba Dome, St. Charles Parish, Louisiana reports the results of the geophysical exploration leading to discovery of the dome and discusses and compares the results of additional exploration, done to define the dome, with the actual dome shape determined from drilling.

Geophysical Exploration in the San Juan Basin.

NEAL CLAYTON, Century Geophysical Corporation, Tulsa, Oklahoma.

Geophysical surveying in the San Juan Basin involves a number of problems peculiar to the area. Magnetometer and gravity meter surveys are complicated by topography and the presence of Tertiary intrusives. Scarcity of water is a major problem for seismic crews. Some arrangements must be made for housing crew employees. Velocity and subsurface control are extremely limited.

Review of Western Canadian Geophysical Activity Since 1948.

H. M. HOUGHTON, Amerada Petroleum Corporation, Calgary, Alberta, Canada.

Geophysical Activity in 1951.

E. A. ECKHARDT, Chairman S.E.G. Standing Committee on Annual Review of Geophysical Activity, Gulf Research and Development Company, Pittsburgh, Pennsylvania.

Development of a New Method of Seismic Velocity Determination.

F. P. KOKESH, Schlumberger Well Surveying Corporation, Jackson, Mississippi.

Considerable interest has recently been aroused in a new method for measuring seismic velocities wherein the explosive charge is placed in the hole and the seismic energy is picked up with detectors placed on the surface. Experimentation carried on during the past year indicates that the new method is quite workable. This paper attempts to outline the basic problem of velocities and their measurement and describes the preliminary development that has been done thus far on the new method of velocity measurement.

Experimental Well Velocity Results Using a Jet Perforator.

MAURICE SKLAR, Union Oil Company, Bakersfield, California.

An experimental velocity survey has been made in a 7,200 foot core hole in Ventura County, California, by firing charges from a McCullough Tool Company Jet Perforator lowered into the hole at various depths and observing travel times to geophones on the surface. The number and size of the charges fired simultaneously varied from two of the 16 gram size to twenty-eight of the 90 gram size. Energy was ample at all depths, although for the 7,200 foot shot it was necessary to estimate the first-arrival time from later phases. The upper portion of the survey made when the hole was 913 feet deep, was duplicated by the conventional method of lowering a geophone into the well and shooting in shot-holes ninety feet from the well. Comparison of results indicates that all first breaks recorded by the conventional method were transmitted through the geophone cable except when the geophone was set on the bottom of the hole.

*Effect of Saturation on the Dilatational Wave Velocity in Rocks.**

D. S. HUGHES AND J. L. KELLY, Department of Physics, The University of Texas, Austin, Texas.

The velocity of dilatational waves in four sandstones and a shale has been measured in the laboratory by high frequency pulse methods previously described. The velocity was measured in both dried and water-saturated cores for each rock. At atmospheric pressure the change in velocity with saturation is not very great but with most specimens the velocities in the saturated rocks are definitely higher. With increase in hydrostatic pressure the saturated cores show relatively little increase in velocity whereas the dry cores show relatively large increases in velocity. For the samples studied at the upper pressure limit of 1,000 bars (15,000 p.s.i.) to dry velocity is always greater than the

* This work was supported by the Office of Naval Research under Contract N6onr-266, Task Order VIII, and by research grants from the Shell Oil Company and the Humble Oil and Refining Company.

saturated velocity. The sandstones used are from widely spaced localities and have porosities in the range 8 to 20 percent. The hydrostatic pressures were held to 1,000 bars to reduce irreversible alteration of cores. These results are compared with past measurements and possible origins of disagreement are discussed.

Procedures for the Direct Employment of Neutron Log Data in Electric Log Interpretation.

M. R. J. WYLLIE, Gulf Research and Development Company, Pittsburgh, Pennsylvania.

It is well known that under suitable borehole conditions there is a relationship between porosity and the deflection of a neutron log curve. This relationship finds practical use, calibration of the neutron deflections being made by reference to porosities measured on cores. It is shown that theoretically core analysis is not mandatory for neutron log calibration and that the calibration may be achieved by direct plotting of suitable neutron and electric log data. For this purpose the concept of the neutron deflection corresponding to a formation factor of unity is introduced. It is shown that this concept makes it possible to use a combination of electrical and radio-activity log data to locate zones of oil saturation in hard rock formations and even to estimate the oil saturation. Application of the method to sandstones is also considered. In oil-base mud logging, neutron-log data may be conveniently combined with resistivities read off induction logs to give information bearing on the location of saturated zones and the estimation of connate water salinities. Finally a combination of electrical and radioactivity log data is theoretically capable of contributing to the quantitative eludication of the "dirty sand" problem.

Carbon 14 Measurements on Geologic Samples.

J. LAURENCE KULP, Lamont Geological Observatory, Columbia University, Palisades, New York

Recent results of the natural radiocarbon content of numerous specimens of geologic interest will be presented. These include late Pleistocene glacial history, deep sea sedimentation, and deep ocean circulation. The geological significance of these results will be discussed.

Bringing People Together.

A. C. BLACKMAN, Division of Industrial Safety, State of California, San Francisco, California.

The advantages of industry-wide cooperation in matters of safety are discussed. Results of several industry groups that have engaged in cooperative safety efforts are presented. Problems encountered in securing group action and the value of a state agency to foster cooperation between large and small operators and their work forces are discussed.

The Results of Cooperative Safety Efforts.

HARRY H. HILLMAN, California Production Service, Inc., Long Beach, California.

The experiences of the American Association of Oil Well Drilling Contractors in setting up their effective safety program are discussed. Many problems faced by this organization in the early stages of their effort are mentioned. Various safety materials such as bulletins and posters that are distributed to the membership in order to keep alive the interest in the safety program are shown. Information is presented to demonstrate the excellent results accomplished due to the efforts of this association.

A Minimum Accident Prevention Program for the Small Geophysical Company.

JOHN F. IMLE, Safety Division, Geophysical Service, Inc., Dallas, Texas.

Recognizing a growing interest in safety on the part of the smaller geophysical companies and their insurers, the essentials of a suggested minimum program are discussed. It is pointed out that the initiation of accident prevention work must be from top management downward through supervisors, party chiefs and key party personnel to the employee. The problem is discussed of maintaining an active safety program at the crew level.

Analysis of Accidents Reported to Accident Exchange Group in 1951.

H. M. THRALLS, Seismograph Service Corp., Tulsa, Oklahoma.

Study of the accidents reported monthly to the Accident Exchange Group reveals a monotonous repetition of a number of accidents month after month. They are repeated with such regularity that it is almost possible to predict the number of wrecked shooting trucks, the number of mashed fingers, and the number of cases of poison ivy that will be reported the following month. Such information if used properly, could be used to eliminate a high percentage of the expectable injuries. This conclusion seems valid because the greatest hazard in seismograph work, dynamite, is responsible for very few accidents. Dynamite is the one hazard upon which accident prevention efforts has been concentrated.

Basic Principle of the La Coste-Romberg Underwater Gravity Meter.

LUCIEN LA COSTE.

The large seismic motion encountered at the bottom of the ocean—often as much as $\frac{1}{8}''$—prevents the use of an ordinary land gravity meter (with remote operating and indicating devices) from being used for underwater work. The beam hits the stops which are necessary to prevent large errors from hysteresis. The La Coste-Romberg underwater instrument meets this difficulty by means of a servo-driven elevator which automatically raises and lowers the whole meter so as to prevent the beem from hitting the stops. This is done in such a manner as to keep the elevator oscillating about a central position so as not to add any net acceleration to the beam reading. An electrical circuit averages the position of the beam, and readings are taken by nulling this average. Readings can be obtained with an accuracy of one-tenth milligal even when the ocean bottom is undergoing vertical seismic motion with a double amplitude of $\frac{1}{8}''$ and a period of 4 seconds. A basic patent has been allowed by the U. S. Patent Office.

Evaluation of Density Data for the Determination of Density Contracts.

RAOUL VAJK, Standard Oil Company of New Jersey.

Density values determined on scattered cores of a well are not sufficient for locating density contrasts in sedimentary strata. However, they can be used for constructing a curve representing the density of shale (or marl) as function of depth. From this curve missing density values of shale can be interpolated. Density values of other alternating sedimentary beds, as sand, sandstone, limestone, etc., do not change considerably with depth and a few density determinations on these samples should be sufficient.

Using the above information and consulting the geological well log, a density value (σ) can be attributed to every stratum, corresponding to its lithological character. Then, the following function is computed:

$$y=\sum_{i=1}^{n}\Delta z_i\sigma_i$$

where Δz is the thickness of the stratum and "n" is the number of the strata. Plotting "y" against "z" (depth) and "breaking" points of the curve, or, the corners of the polygon approximating the curve, mark the depths of density contrasts. The magnitude of the density contrast can be easily computed.

The procedure is illustrated on density data obtained from a 2,000 m deep well.

Some Important Problems Concerning the World-Wide Gravity Program.

W. HEISKANEN, Finnish Geodetic Institute and Ohio State University, Columbus, Ohio.

The principal geodetic purposes of the world-wide gravity program are: to convert the existing geodetic systems into one uniform World Geodetic System; to determine the shape of the geoid; and to check the dimensions of the reference ellipsoid with the help of the existing triangulation methods.

Work done during the past year will be reported and an outline given on what has yet to be done successfully to complete the program. Special mention will be made of the significance of the gravity

measurements at sea; of gravity surveys in some unsurveyed areas; of the most useful reduction of gravity anomalies; and on the connection of the gravity base stations of the world to the same system. The ultimate result of the world-wide gravity study will be discussed. This will be one set of world-maps given the undulations N of the geoid, another set of world-maps giving the meridian component ϵ and a third set giving the east-west component η of the deflections of the vertical. The obvious significance of this work for geophysical investigations will be emphasized.

Characteristics of Electromagnetic Reflections in Conducting Media.

W. JACQUE YOST, R. L. CALDWELL, C. I. BEARD, C. D. MCCLURE, AND E. N. SKOMAL, Magnolia Petroleum Company, Dallas, Texas.

In a recent paper, one of the authors has reviewed the published work relating to the theory of electromagnetic reflections as it applies to a conducting media such as the sedimentary section of the earth's crust. Several necessary extensions of this theory, as reported in that publication, will be briefly reviewed. One result of such a theoretical treatment is that a metallic model of a horizontally stratified section can provide data of considerable value in the interpretation of geophysical data. A description of such a model, in operation in the authors' laboratory, will be given along with slides illustrating its construction and operation. The principal use of this type of metallic model is to provide a rapid, direct means of studying the nature of electromagnetic reflections arising from resistivity contrasts within an otherwise homogenous, conducting medium. The character of various types of reflected signals will be illustrated by means of slides. Graphs and tabular data will be shown to illustrate how such reflected signals depend upon the depth and nature of the reflecting horizon. Finally, data will be presented to show the agreement between such model studies and similar results obtained from known resistivity contrasts in the earth.

The Gulf Airborne Gradiometer.

W. E. WICKERHAM, Gulf Research and Development Company, Pittsburgh, Pennsylvania.

An instrument capable of measuring magnetic gradients as encountered in airborne magnetometer operations has possible applications as an interpretational aid. Its usefulness, particularly for qualitative analysis, will be discussed briefly. The design of a spatial-type airborne gradiometer of adequate precision can be shown to be quite impractical. An instrument based on the time derivative of the magnetic intensity variations provides a useful alternative and will be described.

An Application of Punched Card Methods in Geophysical Interpretation.

PAUL W. FULLERTON, Applied Science Department, International Business Machines Corporation, Tulsa AND JOSEPH A. SHARPE, Frost Airborne Survey Corp., Tulsa.

There is a large class of problems in geophysical interpretation which is solved by the integral over a plane surface of the product of an observed field value or an assumed surface density of some characteristic property F by a weighting function W,

$$S(x, y, z) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} F(x\text{-}u, y\text{-}v, o) W(u, v, z)\, du\, dv$$

Use of a trigonal coordinate system and substitution of finite sums for the infinite integrals leads to a particularly useful form of adequate practical accuracy, for calculation by punched card methods.

The geophysical interpretation problems to which this attack applies will be listed, and an illustration will be given of the calculation of the second vertical derivative of magnetic total intensity by employment of the widely available I.B.M. punched card machines.

A Seismic Velocity Logging Method.

C. B. VOGEL, Shell Oil Company, Houston, Texas.

A well logging method is described which measures seismic velocity as a function of depth. The method uses a transient sound pulse, thus making possible the resolution of shear waves. Various

systems of sources and receivers for minimizing bore hole errors are discussed. With the most elaborate system considerable accuracy is obtainable in the face of large bore hole diameter variations.

Seismic Recording on Magnetic Tape.

G. B. LOPER AND R. R. PITTMAN, Magnolia Petroleum Company, Dallas, Texas.

A system of recording and reproducing exploration seismograms on magnetic tape is described. Geophones and amplifiers with broad band response, approximately 4-300 cps, are used to channel the seismic signals to a 13-track tape recorder. The magnetic tape is 1-inch wide. Some narrowing of the band-width at both high and low frequency ends is done to suit the particular studies to be made. One of the tracks is used to record a time reference signal. Each broad band recording is formed into an endless loop and played back in repeating fashion. The signals are fed through a flexible system of filtering and mixing, then examined on the screen of a 12-trace cathode-ray oscilloscope of 12-inch diameter. The sweep of the oscilloscope is synchronized with the loop and, by varying the sweep speed, the entire record, or an expanded portion thereof, is held stationary on the screen. Conventional paper records to be reproduced, modified record are finally made with a regular seismic camera.

Deep Sea Refraction Techniques and Measurements in the Atlantic Ocean.

MAURICE EWING, CHARLES B. OFFICER, PAUL C. WUENSCHEL, BRUCE C. HEEZEN AND GEORGE SUTTON, Lamont Geological Observatory, Columbia University, Palisades, N. Y.

During the Summer of 1950 and the Spring of 1951 refraction cruises were made by the members of the Lamont Geological Observatory on the research vessels *Atlantis* and *Caryn* of the Woods Hole Oceanographic Institute. A total of one hundred and three refraction stations were made in the Western Atlantic and Caribbean on these cruises. On all the deep water stations (more than 1,000 fathoms) a determination of basement velocity and depth was obtained and in all cases the basement had a velocity corresponding to the Intermediate layer of earthquake seismology. About a third of the profiles were carried out far enough to locate the Mohorovicic discontinuity and determine the velocity of *Pn*. These results are discussed in detail elsewhere. A description is given of the two ship deep sea refraction operation. The equipment, the reasons for its design, and what it accomplishes are discussed as well as the hydrophone handling and shooting technique.

Gulf Coast Surface Waves.

L. G. HOWELL, E. F. NEUENSCHWANDER, AND A. L. PIERSON, III, Humble Oil and Refining Company, Houston, Texas.

A study has been made of surface seismic waves in the Gulf Coast area near Houston, Texas. Recordings have been made with a long period seismometer of the vertical displacement type, and also with a three-component seismometer of the velocity type. In an analysis of dispersion of Rayleigh waves, both a high-frequency and a low-frequency train have been observed in the same time interval as predicted by theory. According to Ewing, the high-frequency branch has been recorded before on water-covered areas but not on land.

Interpretation Method for Well Velocity Surveys.

DEAN WALLING AND CARL H. SAVIT, Western Geophysical Company, Los Angeles, California.

A method is presented whereby the problems of "cable lead" and of extraneous energy paths in general may be solved within the framework of contemporary conventional procedures. The method is illustrated by an actual survey and by laboratory tests.

Application of the Reflection Seismograph to Near-Surface Exploration.

C. F. ALLEN, L. V. LOMBARDI AND W. M. WELLS, Stanford Research Institute, Stanford, California.

The geophysical approach to very shallow exploration problems has been limited, in the main, to electrical, magnetic, and refraction methods. The reflection seismograph, with its clear advantages

of decreased ambiguity and increased resolving power can be applied to many of these problems. In the fall of 1951, a Stanford Research Institute crew conducted an experimental reflection survey in Minnesota, mapping with correlation spreads the glacial drift-bedrock interface along seventy miles of line. The interface varied in depth below surface from 260 to 610 feet, and control core holes showed the seismic profile to be essentially correct, where checked. Over-all velocities, determined by shooting core holes, varied from 3,800 feet per second to 5,500 feet per second. Special instrumentation included a high speed camera and a filter peaked at 100 cps. All shots were fired in the air. The method has obvious applications to mining, engineering, and ground water problems, and to difficult weathering problems involving thick alluvial, eolian, or glacial debris.

Recent Developments in Mining Geophysics.

HANS LUNDBERG, Lundberg Explorations, Ltd., Toronto, Ontario, Canada.

Except for developments in interpretation technique the magnetic methods have remained the same. Many times it is found easier to do the magnetic survey from the air with flight profiles at different altitudes to enable the interpreter to calculate depth and dimensions of magnetic bodies. In the electromagnetic field the instrumentation has been improved to such a detree that direct measurements of the secondary fields are possible. This has opened the possibility for making electromagnetic surveys from airplanes, and, even if a great deal more work remains to be done, it is now possible to survey mining fields and outline more important bodies of higher conductivity. The third method, radioactive, has been airborne for some time, and mostly owing to the use and development of field scintillation counters it has been possible to reconnoiter and also survey in detail from the air, mining regions and outline bodies of high radioactivity. Recent drilling has confirmed such indications and proven the surveys to be very accurate.

Subsurface Gravity Measurements.

GEORGE R. ROGERS, Phelps Dodge Corporation, Douglas, Arizona.

Gravity data were obtained at approximately 100-foot intervals in a vertical mine shaft 2,916 feet deep. The shaft passed through a region of high positive density contrast, and a local anomaly was observed of plus 14.0 gravity units to minus 17.9 gravity units. Calculations for Bougeur densities were carried out with the gravity measurements. A theoretical sphere that closely approximates the observed data and known conditions is derived from the gravity data.

Model Studies of Electromagnetic Prospecting Methods.

L. B. SLICHTER AND L. KNOPOFF, Institute of Geophysics, University of California, Los Angeles.

Current results are reported concerning the detection of idealized conducting ore-bodies by several different types of electromagnetic prospecting methods. The studies are being conducted by the use of scale models, in the laboratory, under appropriate conditions of electromagnetic similitude. The working region consists of a tank $12' \times 7' \times 4'$ containing water or salt water, representing a homogenous country rock in which "model ore-bodies" of elementary form and type are immersed. At the frequency of 200,000 cycles now in use the geometric scale-factor between model and prototype is of the order of 1:200. Initial results are shown in which are compared the detection of the same simple conductors by means of four different types of field procedures. The model laboratory is serving a practical need as a convenient means for investigating many interesting questions in electromagnetic prospecting.

Magnetic Susceptibility Measurements in Minnesota.

HAROLD M. MOONEY AND RODNEY L. BLEIFUSS, University of Minnesota, Minneapolis, Minnesota.

Susceptibility determinations have been made on 200 outcrops of eleven rock types, using a three-coil induction instrument. Measurement is effective over a hemisphere of 50 cm radius. Data are

given to show that the instrument is much less sensitive to rock surface irregularities than any previously described. Measuring circuits consist of 950 cycle oscillator, mutual inductance bridge, and two-stage amplifier. Investigation of errors shows that surface irregularities remain most important. Calibration by calculation is checked against ferric chloride standards through small samples taken at each outcrop. Data are given to show: (1) calculated calibration is satisfactory, and (2) small sample variability is larger than large sample variability. Magnetite content, determined by magnetic separation and chemical analysis is plotted against susceptibility.

Ore Body Size Determination in Electrical Prospecting.

HAROLD O. SEIGEL, Newmont Exploration, Ltd., Jerome, Arizona.

A method of size determination is presented which utilizes the primary voltage disturbance created by the body and the variation of the disturbance with electrode spacing. The form of the disturbance function is compared with the theoretical curves based on the oblate spheroid.

The Cylindrical Ore Body in the Presence of a Cable Carrying an Oscillating Current.

JAMES R. WAIT, Newmont Exploration, Ltd., Jerome, Arizona.

The problem of an infinite cable carrying an oscillating current parallel to a conducting cylinder is solved. The homogenous electrical properties of the media inside and outside the cylinder can be arbitrary. The special case is considered in detail where the exterior medium is a relatively poor, conducting medium. The application to geophysical prospecting for massive sulphide ore zones is discussed.

SIXTH AWARD OF HONORARY MEMBERSHIP
CITATION

SIGMUND HAMMER

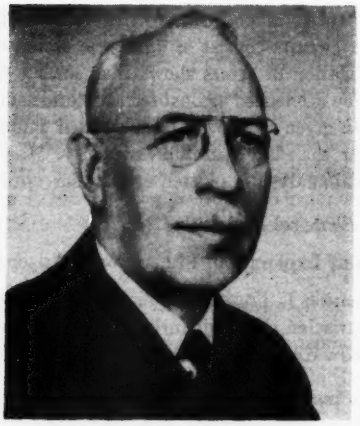
The highest honor the Society of Exploration Geophysicists can bestow in recognition of long and outstanding achievements and contributions in the field, geophysical exploration, is an Honorary Life Membership in the Society.

Each year the Society's committee on Honors and Awards examines the membership rolls to see if anyone among the members deserves to be so honored. Four times during the 22 years of the Society's existence this has been done. This year the Honors and Awards Committee has recommended that a fifth Honorary Membership should be awarded, and this recommendation has been unanimously approved by the Executive Committee and the Council of the Society. It gives me deep personal pleasure and a high sense of official appreciation to have the distinguished honor to present this award at this time. The recipient is Dr. E. A. Eckhardt, vice president, assistant director and staff geophysicist of Gulf Research and Development Company, Pittsburgh, Pennsylvania.

Dr. Eckhardt has had a long and distinguished career in Geophysical Exploration and has pioneered its development since its inception in this country. In 1920 he gave a talk on Geophysical Exploration before a colloquium of geologists at the U. S. Geological Survey. This is probably the first talk on this subject delivered in the Western Hemisphere. In the following years, not excluding the present, he has been a leader in developing and promoting Geophysical Exploration to its present stature of world importance.

Dr. Eckhardt, the Society of Exploration Geophysicists awards an Honorary Membership to you in official and public recognition of its debt to you for your outstanding interest in its affairs since its inception, for your contributions to the development and improvement of several important geophysical exploration techniques, for your administrative genius in developing men, and for your effective leadership in promoting wholesome cooperation between geologists and geophysicists.

In grateful recognition of your many contributions to geophysical exploration, we welcome you to join the small and distinguished roll of honorary membership in the Society of Exploration Geophysicists.



DR. E. A. ECKHARDT
Recipient, Sixth Award of Honorary Membership
March 25, 1952

Sixth Award of Honorary Membership for Outstanding Service to Exploration Geophysics; Doctor Eckhardt (right) receives the certificate from Doctor Hammer

AWARD FOR BEST PAPER OF 1951

SEISMIC VELOCITY AS A FUNCTION OF DEPTH AND GEOLOGIC TIME
Geophysics, Volume Sixteen

DR. LAWRENCE Y. FAUST
Recipient, Award for Best Paper of 1951

Dr. Faust (right) receives the Certificate and Plaque
from President Hammer

NEW RADIO PROPAGATION DISTURBANCE WARNINGS

Beginning July 1, 1952, the National Bureau of Standards will broadcast new short wave radio disturbance forecasts via the NBS standard frequency broadcasting station WWV. This new service will replace the radio disturbance warning notices that have been transmitted by WWV since 1946. The broadcasts will tell users of radio transmission paths over the North Atlantic the condition of the ionosphere at the time of the announcement and also how good or bad communication conditions are expected to be for the next 12 hours.

The NBS radio disturbance forecasts, prepared four times daily, will be transmitted in Morse code twice each hour—19½ and 49½ minutes past the hour—on WWV standard frequencies of 2.5 5, 10, 15, 20, and 25 Mc, as was done prior to July 1. As in the past, the notices will include a letter indicating present radio reception conditions. *However, the new notices will also contain a digit indicating the expected quality of future reception.* As before, the letters used will be "N," "U," and "W," signifying that radio propagation conditions are normal, unsettled, or disturbed, respectively. The digit will be the forecast of expected quality of transmitting conditions on the NBS-CRPL scale of 1 (impossible) to 9 (excellent).

Digit (*Forecast*)	*Propagation Condition*	*Letter* (*Current*)
1	Impossible	W
2	Very Poor	W
3	Poor	W
4	Fair to Poor	W
5	Fair	U
6	Fair to Good	N
7	Good	N
8	Very Good	N
9	Excellent	N

If, for example, propagation conditions at the time the forecast is made are normal but are expected to be only "fair to poor" within the next 12 hours, the forecast statement would be broadcast as N_4 in Morse code, repeated five times, i.e., "N_4, N_4, N_4, N_4, N_4."

PERSONAL ITEMS

GERALD H. WESTBY, president of Seismograph Service Corp., attended the International Hydrographic conference at Monte Carlo, Monaco, April 29 through May 10. The conference, comprised of official representatives of twenty-one maritime union member nations, is held once every five years to exchange ideas on mapping the ocean floors and on general problems of navigation.

The geophysical section of the Anglo-Iranian Oil Company's research station at Kirklington Hall is now in the midst of one of its busiest periods; new equipment is being tested in the grounds of the Hall for a seismic survey of an area east of Nottingham—the first to be carried out in Great Britain since that at Formby, Lancashire, two years ago.

The results of former surveys which covered important areas of the East Midlands have been studied. Geological examinations are now being made of the various prospects which have come to light, in order to assess their value as possible sites for test drilling. Previous search produced evidence of oil in small quantities over a wide area outside the developed fields and it is hoped that a new drilling program will emerge to follow up some of these indications.

RICHARD WILLIAMS announces the organization of Seismic Incorporated, with offices at 4107-A East 11th Street, Tulsa, Oklahoma. The company specializes in reflection seismic surveys, reinterpretation, and consulting work. Williams, company president, resigned the position of supervisor of domestic operations for Century Geophysical Corp. where he had been employed four years, to establish the new company. Previously he had served as national supervisor for Geophysical Service

Inc. and as partner and vice president of Seismic Engineering Co. CYRIL B. SMITH, vice president of the company, was formerly with The Atlantic Refining Co., National Geophysical Co., and was division geophysicist for the Midcontinent and Rocky Mountain area for Sohio Petroleum Co. with offices in Oklahoma City.

PAUL D. BALBIN has been named to head geophysical operations in the North Texas-New Mexico division of Stanolind Oil & Gas Co. Division headquarters are in Fort Worth, Texas.

J. E. LEE, JR. and ROBERT L. SUGGS were named vice presidents of Petroleum Bell-Helicopter Services, Inc., 3503 Fern Street, New Orleans, Louisiana, at a recent meeting of the Board of directors, M. M. Bayon was elected president of the company.

G. D. LARSON has been promoted to supervisor for Kansas operations of Southern Geophysical Co., with offices in Great Bend. JOHN N. BOTKIN has recently returned after 14 months in Korea, where he was a major in the corps of engineers. Botkin has been on the Southern staff for five years and is being advanced to assistant supervisor based in Billings, Montana. W. W. DEAVER, who joined Southern four years ago, has been promoted to assistant supervisor in the Florida-Alabama area.

SIDON HARRIS announces that Southwestern Consultants, Inc., a contract seismograph firm with six crews, has moved its central office from Tulsa to Fort Worth, Texas. Harris was recently named president of the company. G. C. SHIVERS, JR., is executive vice president and is stationed in the Rocky Mountain division offices in Denver. ELMER F. BLAKE and SHIVERS are on the board of directors, of which HARRIS is chairman.

CHARLES M. MOORE, JR., announces the formation of Geophysical Service International Corp., 706 Ninth Avenue West, Calgary, Alta., Canada. The company has taken over all operations of Geophysical Service Inc. in the Dominion of Canada and will be under the resident direction of MOORE, as vice president and manager. Supervisory personnel include T. A. HALBROOK, E. A. KIESLER, R. H. RAINEY, and J. L. STEPHENS. W. E. DICKSON is equipment supervisor and JACK L. CLARK continues as office manager.

DR. JOHN A. ERDELYI-FAZEKAS has been promoted, upon recommendation of the President of the University of Oklahoma to Associate Professor of Geology and Petroleum Geophysicist.

C. W. PAYNE has resigned the position as Division Geophysicist for the Pure Oil Company to open a geophysical consulting office at 1223 Fair Building, Fort Worth, Texas.

HARLUF C. PETERSEN, a native of St. Paul, Minnesota, has been elected a vice president of Freeport Sulphur Company by the company's Board of Directors. Mr. Petersen is a graduate of the Minnesota School of Mines. He became associated with Freeport Sulphur Company in 1934 at the Grande Ecaille, Louisiana, mine. After working in the company's production operations, he became superintendent of Land and Exploration. When Freeport entered the oil and gas field in 1949, he was put in charge of the program, with headquarters in Houston, Texas, where he now lives.

HARRY M. COOPER resigned from Deep Rock Oil Corporation in July to accept the position of Assistant Chief Geophysicist in charge of the Denver division of the Chicago Corporation with offices at 528 Symes Building, Denver 2, Colorado.

J. B. JACKSON has been transferred from Brunei, British Borneo, to Holland and may be addressed at 69 Alkemadelaan, The Hague, Holland.

Calgary, Alberta was the scene of a four-day indoctrination session from April 30 through May 3, sponsored by Geophysical Service International Corporation for twelve students from the University of Toronto. This session marked the inauguration of the first Cooperative Summer Plan between GSI and the University whereby students preparing for careers in petroleum exploration are offered the opportunity to obtain practical experience and an introduction to geophysical prospecting by

serving in helper positions on GSI field crews during the summer months. The indoctrination session was intended as a thorough preparation for summer work and consisted of lectures on various phases of geophysical exploration and its place in the petroleum industry. Speakers at the session included eight leaders from as many oil companies, in addition to GSI personnel. A second abbreviated indoctrination session will be held on May 26 and 27 at Calgary for a smaller group of students from the University of Toronto who are participating in the plan but were unable to attend the first meeting.

JOHN M. DONNA has been promoted from Computer to Party Chief of Geophysical Service Inc. and is taking over a crew in California.

NEIL W. MANN has been elected Vice President in charge of South American operations of Geophysical Service Incorporated. In his new position he will participate in developments in other countries of South America in addition to Brazil, where he has had his headquarters for the past few years. Succeeding Mann as Manager of Brazil operations for Geophysical Service Incorporated is A. M. EICHELBERGER, JR., with office at Avenida 13 de Maio 13, Edificio Municipal 1919, Rio de Janeiro.

Geophysical Service Inc.'s second Summer Cooperative Work Plan was initiated with an orientation session in Dallas June 11–13 for more than twenty students from Massachusetts Institute of Technology, University of Massachusetts, Harvard, Colorado School of Mines, and University of North Dakota. This is a continuation of the program launched last year with MIT whereby students in geophysics and geology are provided an opportunity for practical experience by working on GSI field crews during the summer months. The orientation session consisted of lectures and demonstrations by GSI members and local leaders in the petroleum industry, which were designed as an introduction to the summer's work.

WILLIAM HOWARD MYERS has resigned his position as Chief Geophysicist with Union Oil Company of California and Calgary, Canada to enter the consulting field in that city. Prior to his position with Union Oil Company, Mr. Myers was manager for United Geophysical of Canada and Alaska. His address is 926 Ridge Road, Calgary, Alberta.

PAUL CHARRIN announces the removal of his office from 1013 Union National Bank Building to 402 Melrose Building, Houston, Texas.

A. M. EICHELBERGER, JR. has recently resigned his position of Senior Research Physicist with the Field Research Laboratories of Magnolia Petroleum Company, Dallas, Texas, and is now residing in Rio de Janeiro, Brazil, where he is Division Manager for Brazil for Geophysical Service Incorporated of Dallas, Texas.

The Lane-Wells Company is sponsoring a Technical Paper Contest for Petroleum Engineering students of ten universities and colleges throughout the United States and Canada.

Lane-Wells is celebrating its 20th year of service to the Petroleum Industry, and presenting this event for the benefit of the Industry and the Petroleum Engineering students who will some day be a part of it. Those eligible are undergraduate or graduate students in Petroleum Engineering who are regularly enrolled at Agricultural and Mechanical College of Texas, Colorado School of Mines, Louisiana State University, Pennsylvania State College, Tulsa University, University of Alberta (Canada), University of California, University of Oklahoma, University of Southern California, or University of Texas.

A $200 First Prize and $100 Second Prize will go to the authors of the best papers presented at each school. The winning papers of each school will be collected, bound and distributed to the Petroleum Industry and participating universities.

The contest is open now. Complete details can be obtained from the Head of the Department of Petroleum Engineering at each of the schools listed above.

All members of SEG are geophysicists.
Are all geophysicists members of SEG?

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GEOPHYSICS

A Journal of General and Applied Geophysics

AN ANALYSIS OF AIRBORNE SURVEYING FOR SURFACE RADIOACTIVITY*

JOHN C. COOK†

ABSTRACT

Quantitative estimates of the gamma radiation field intensities expected to be encountered in flight over various geologic bodies are presented. Scattering effects are included in the calculations, but several simplifying assumptions were necessary, such as assigning equal energies to all photons. Results are compared with geiger counter measurements of three kinds: near a small natural carnotite deposit, near a tenth-curie of radium, and soundings made over normal terrain at various times. It appears that anomalies from most outcrops of radioactive ores will exceed the normal fluctuations of background radiation due to topography, variations of composition of the surface, etc., only at flying altitudes of less than about 35 feet. However, such anomalies can probably be detected under favorable conditions by their characteristically pointed shape, allowing flight at higher elevations. Requirements on flight plan and instrumentation are discussed.

INTRODUCTION

Airborne radioactivity surveying methods have been under development by various private and governmental groups since about 1943 for use in fast and efficient reconnaissance for uranium ores (Stead, 1950; A. H. Lang, 1950). Much of the work done has been of a practical nature, including particularly the development of suitable instrumentation. The research reported here was undertaken to provide an approximate, quantitative description of the earth's gamma-radiation field, the total intensity of which is the quantity generally profiled in airborne surveying.

The results permit formulation of a few tentative principles to guide the planning, execution, and interpretation of such surveys. They also suggest another possible application of this relatively new geophysical tool in geological contact mapping from the air. Anomalous radioactivity in the soil overlying petroleum reservoirs has been reported (Stothart, 1950; Bernard Lang, 1950), but because little quantitative data are available, and since those mechanisms so

* Adaption from a doctorate dissertation, Division of Geophysics and Geochemistry, The Pennsylvania State College, 1951. Microfilm copy of the original manuscript (no. 3283), 157 pp., available at $1.96 from University Microfilms, Ann Arbor, Michigan. Presented at the Houston regional meeting May 30, 1952.

† Southwest Research Institute, San Antonio, Texas.

far proposed to account for such an association of petroleum with surface radioactivity (Tripp, 1947) seem to be highly speculative, the application of airborne radioactivity surveying to petroleum prospecting will not be considered at the present time.

The penetrating radiation traversing the atmosphere is well known to consist of several components from various sources:

(1) Gamma rays from uranium, thorium, potassium, and their decay products in soil and rock near the surface of the ground.
(2) Gamma rays from atmospheric radon and less important elements.
(3) Cosmic rays of various kinds.
(4) Gamma rays from synthetic radioactive isotopes contaminating the air, atmospheric precipitation, and the ground (Herzog, 1946; Meinke, 1951).

The instruments used for profiling the intensity of component (1), coming from the ground, will generally also register all other components. This is undesirable, since variations in these extraneous radiations will be recorded as misleading false anomalies. It is necessary to know the expected relative magnitudes of the various components and, if necessary, to eliminate or correct for the extraneous ones.

Calculations of components (1) and (2) will be made, reliable as to order of magnitude or better, using the extensive published data available (checked by special experiments) for the gamma radiating power of rocks and soils and for the radon content of the atmosphere. The complicated gamma-ray spectra of the natural radioactive elements will not be considered in the calculations, since the weak but numerous "soft" rays are filtered out relatively close to the source, leaving chiefly the more highly penetrating photons from radium *C* (having energies of 1.4, 1.7, and 2.2 mega-electron-volts), thorium *C* (2.6 Mev) and potassium 40 (1.8 Mev). Precise calculations are neither possible at present nor necessary to an understanding of the principal features of the natural gamma radiation field.

FIELD INTENSITY CALCULATIONS

Eve (1911) made calculations of the gamma-radiation intensity from two extended sources, the earth and the atmosphere. He assumed an exponential law of absorption for gamma rays. Recent experimental work (White, 1950) and theory (Corner, Day and Weir, 1950) shows that the radiation from a point source immersed in a scattering medium of large size may be ten or more times that calculated for simple exponential absorption (using the accepted absorption coefficients, measured with collimated radiation) at moderate distances. The intensity in terms of "flux units" (photons per sec traversing a sphere of 1 cm^2 projected cross-section) can more accurately be expressed:

$$\phi = \frac{S}{4\pi R^2} e^{-aD}. \qquad (1)$$

Where S = rate of photon emission from the source,
R = distance to the source.

The exponential α is about 0.7 and varies slightly with the distance $D=\mu R$ in "mean free paths" and with the initial mean gamma-ray energy, where μ is the compton "absorption" coefficient for direct (collimated) rays, such as is given in all standard tables.

It is necessary to introduce here a first approximation. The "average" energy of natural gamma radiation will be assumed to be 1.8 Mev, which represents uranium and potassium satisfactorily. For the 2.6 Mev rays of thorium, all calculated intensities will be too low by the order of 10 percent. For 1.8 Mev gamma rays, α can be expressed approximately by an empirical formula fitting the tabulated values given by Corner, Day, and Weir (1950):

$$\alpha = 0.116 + 0.0977 \log_e (100D). \tag{2}$$

Also for 1.8 Mev rays, the "absorption" coefficient has values calculated by Plesset and Cohen (1951) to be about as follows:

μ = 0.0000594/cm for air (of standard density),

μ' = 0.1125/cm for earth of density 2.25 gm/cm^3 (assumed composed of SiO_2).

These formulas and constants will be used to calculate the radiation intensities from various extensive natural sources, as follows:

(a) The atmospheric radon, assumed homogeneous.
(b) A small source embedded in a flat earth.
(c) A line-source embedded in a flat earth.
(d) A semi-infinite radioactive flat half-earth bounded by a linear edge.

These ideal cases, or combinations of them, simulate the majority of situations likely to be encountered in prospecting. Following the practice of Eve, most integrations will be performed graphically with a planimeter, the graphs themselves serving to illustrate several important points.

ATMOSPHERIC RADON

For a volume element dv the "source strength" S of equation (1) is: $S=qsdv$. The average radon content of the lower atmosphere, q, is given by Preibsch, Radinger, and Dymak (1937) as 3 to 300×10^{-17} curies Rn/cm^3 and s is given by Fearon (1949) as (3.7×10^{10} hard gamma rays)/(sec$\times$curie radon). A semi-spherical shell of radius R and thickness dR, truncated by the earth's surface and with its center at the airborne radiation detector, is chosen as the volume-element. Where h is the height of the center above the surface (assumed plane), the formula for the volume element (derived from Eshbach, 1936, page 2–43, example 38) is: $dv=4\pi R^2(R+h)dR/(2R)$ for the range $0<h<R$. Combining this expression with (1) and with $S=qsdv$, the total flux at the detector, due to the entire atmosphere, becomes

$$\phi = \int_0^{R>>h} \frac{e^{-\alpha D}}{4\pi R^2} qs\,dv = qs \int_0^h \frac{dR}{e^{\alpha\mu R}} + qs \int_h^{R>>h} \frac{(R+h)dR}{2Re^{\alpha\mu R}}. \qquad (3)$$

The integrand is plotted *vs.* R for various values of h in Figure 1. It is seen that, at heights beyond $h=300$ meters, the area under the curve is nearly independent of height. There is very little contribution to the area (the integral) from shells of air beyond about 800 meters from the detector. The integral for $h=0$ (detector on the ground) is just half that for $h=\infty$, as it should be.

Values of ϕ found by substituting the constants q and s and the areas from Figure 1 (in meters) into Equation (3) are given as a function of height h by two

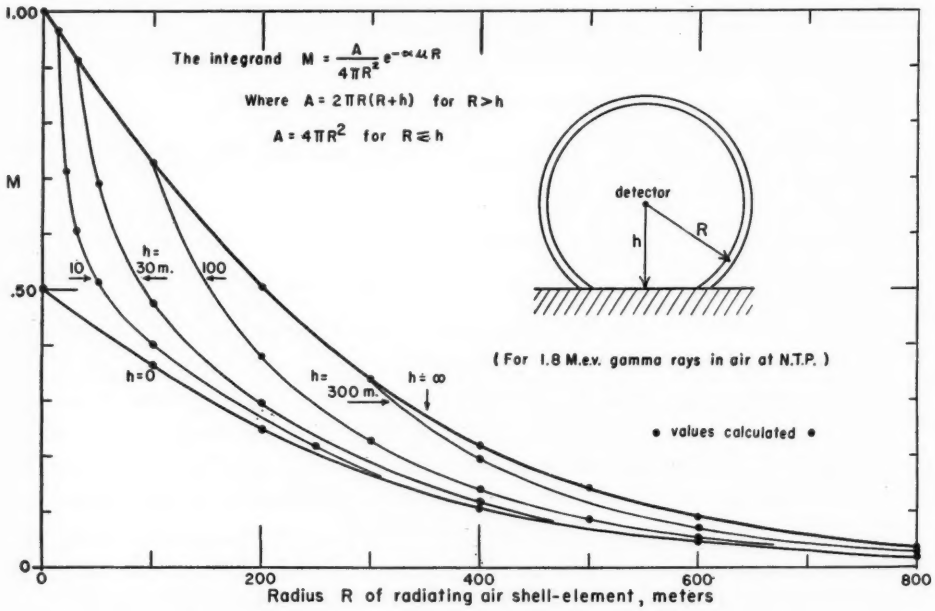

FIG. 1. Graphical integrals of the Atmospheric Radon Effect.

dot-dashed curves in Figure 9. The value of q assumed for each curve is given in the figure. It can be anticipated that the flux from atmospheric radon will generally lie between these extremes.

A SMALL EMBEDDED SOURCE

Exposures of carnotite, pegmatite enrichment zones, and weathered outcrops or residue from pitchblende contain radioactive elements distributed throughout a solid medium highly absorbent to gamma rays. The radiation escaping from the surface and reaching the airborne detector will consist partly of photons scattered within the soil or rock surrounding the source volume-element. An approximate method of taking account of both earth and air upon the radiation intensity is to measure the total distance from source to detector in "mean free

paths" where one mean free path in earth is $1/\mu' = 8.9$ cm and one mean free path in air is $1/\mu = 168$ meters. The exponential scattering function α will be given by equation (2) where D is now given by:

$$D = \mu \text{ (air path length)} + \mu' \text{ (earth path length)} \tag{4}$$

To set up the necessary triple integral consider the general case of a rectangu-

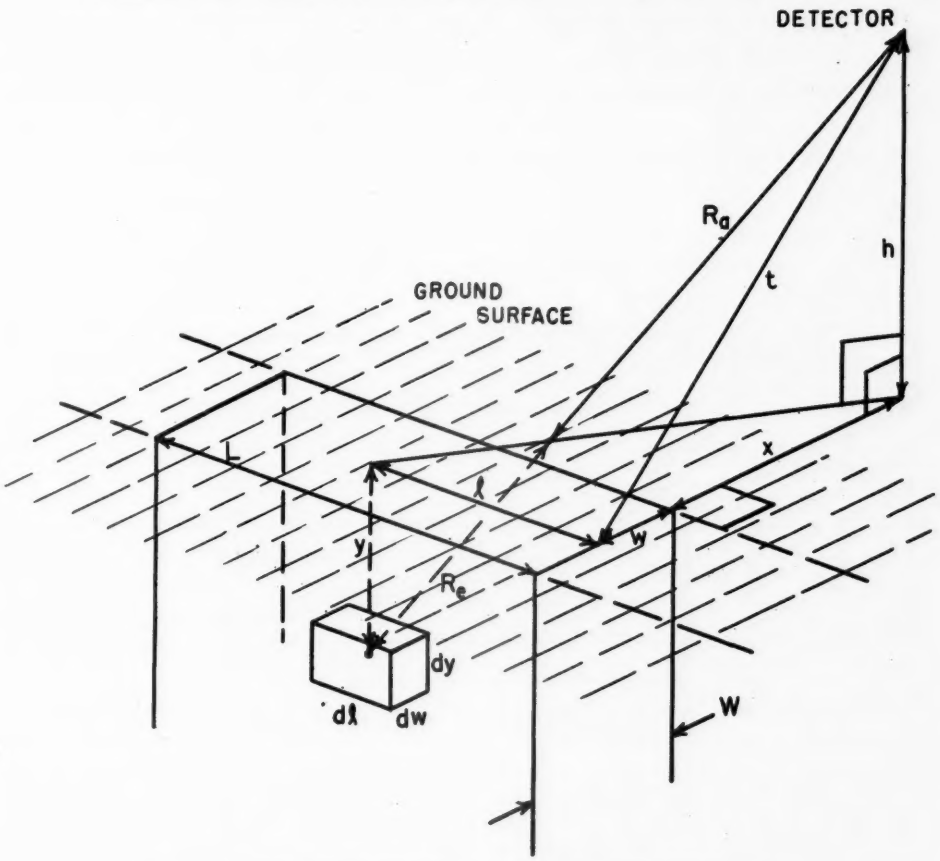

FIG. 2. Geometry and symbols for outcropping solid γ-ray source.

lar body of radioactive material of large vertical extent Y, set flush with the ground surface as in Figure 2. Here the total distance R from volume element $dw \cdot dl \cdot dy$ is in earth for a distance $R_e = yR/(y+h) \doteq y\,R/h$ and in air for a distance $R_a = hR/(y+h) \doteq R$. The approximations are justified by the fact that very little of the total radiation escaping into the air comes from depths below $y = 0.3$ meter, as will be seen, whereas flying height h is generally at least 3 meters, so that $h \gg y$. Noting also that

$$R^2 \doteq l^2 + h^2 + (x + w)^2 = l^2 + t^2,$$

the integral desired is

$$\phi \doteq \frac{cms}{4\pi} \int_0^W \int_0^L \frac{e^{-\alpha\mu R}}{R^2} dw \cdot dl \int_0^Y e^{-\alpha\mu' yR/h} dy, \tag{5}$$

where c is the concentration of radioactive material in grams per gram of rock, m is the density of the source rock, and s is 3.7×10^{10} photons/(sec×gm Ra) or 13,300 photons/(sec×gm U) from Fearon (1949).

That part of the integrand containing y also depends upon α, which is a slowly varying but complicated function of y (see Eqs. 2 and 4). Substitution

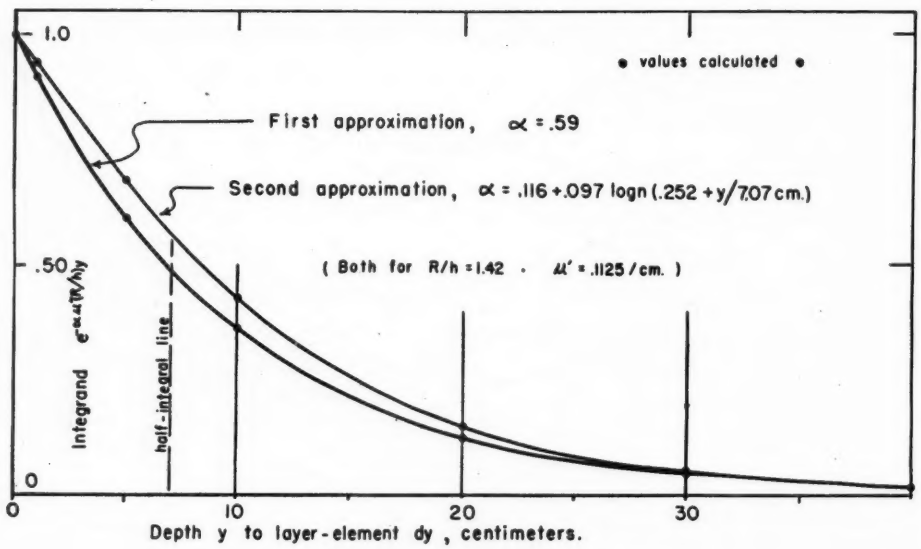

FIG. 3. Trial integrations in depth, for solid source.

would yield an unmanageable transcendental integrand. However, a suitable constant, average value of α should yield a sufficiently accurate integral. Trial integrations were made graphically for the particular case $R/h = 1.42$. The two curves are shown in Figure 3. In one trial α was fixed at 0.59 while in the other it was allowed to vary with y, choosing the air part of the path as 168 meters ($\mu R = 1$). The latter gave an integral only 8 percent greater than the former, so that considering α fixed for this integration is probably accurate enough for the present problem. Figure 3 also shows which layers (dy) of the radioactive body contribute most of the radiation to the field above the ground. It is seen that about half the area (integral) under each curve is contributed by layers of soil or rock from the surface down to about $y = 7$ cm, and that layers below $y = 30$ cm contribute very little. Hence the average path length in earth is of the order of one "mean free path."

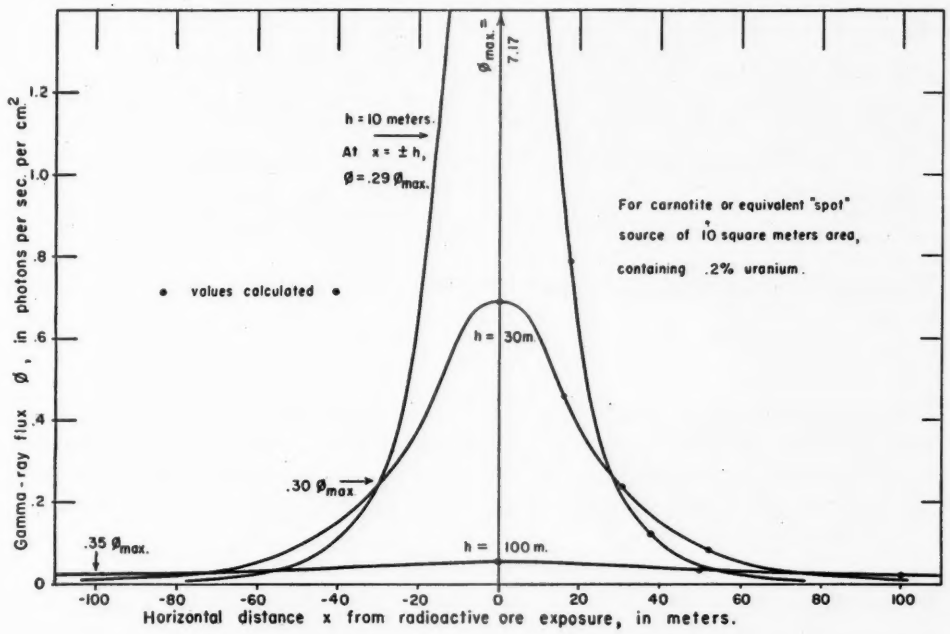

FIG. 4. Computed radiation flux for a small embedded source.

If α is assumed practically independent of y, one integration of (5), taking the upper limit $Y \gg 1/\mu'$, produces

$$\phi \doteq \frac{cmsh}{4\pi\mu'} \int_0^W \int_0^L \frac{e^{-\alpha\mu R}}{\alpha R^3} \, dw \cdot dl. \tag{6}$$

For the majority of "spot exposures" of radioactive ores, the dimensions are small compared to practical flying heights h, so that R and α are nearly independent of w and l. The integrations of (6) can then be performed by multiplying the coefficients and integrand by the area WL of the outcrop. The resulting function, calculated for a varying α found from (2) with $D=(1+\mu R)$, is plotted *vs* x in Figure 4 for three values of h. A reasonable exposure area $WL=10$ square meters and a representative uranium content $m=0.002$ gm U/gm were assumed. Note the rather pointed shape characteristic of the flux profiles over such anomalies. At horizontal distances $x=h$ from the exposure, the anomaly reaches about 0.3 of full value. The peak values shown in Figure 4 are plotted *vs.* flying height in Figure 9.

THE EFFECT OF BURIAL

Comparatively non-radioactive foreign cover (glacial drift or soil) over a spot exposure of radioactive ore will reduce the maximum anomaly found by approximately the factors given in Table 1:

TABLE 1

ANOMALY REDUCTION FACTORS FOR COVERING SOIL

Soil Depth d	Cms	11	24	35	45	59	69	80	94	104
	Inches	4.3	9.5	14	18	23	27	32	37	41
multiply anomaly max by $f=$		0.5	0.2	0.1	0.05	0.02	0.01	0.005	0.002	0.001

These factors were computed from a function consisting of the attenuation factor of (1):

$$f = e^{-\alpha\mu' d} \tag{7}$$

assuming a constant $\alpha = 0.59$ and $\mu' = 0.1125$ cm for an average soil. Table 1 shows that a 10 square meter pitchblende deposit averaging 2 percent uranium buried by about a foot of nonradioactive soil would give an anomaly no larger than shown in Figure 4 for a carnotite exposure of similar size.

A LONG LINEAR EMBEDDED SOURCE

By substituting $R^2 = (l^2 + t^2)$ in (6) and plotting the integrand *vs.* l (letting α depend upon R as before with Figure 4), the curves of Figure 5 are obtained for various values of slant-distance t to the nearest part of the rectangular exposure

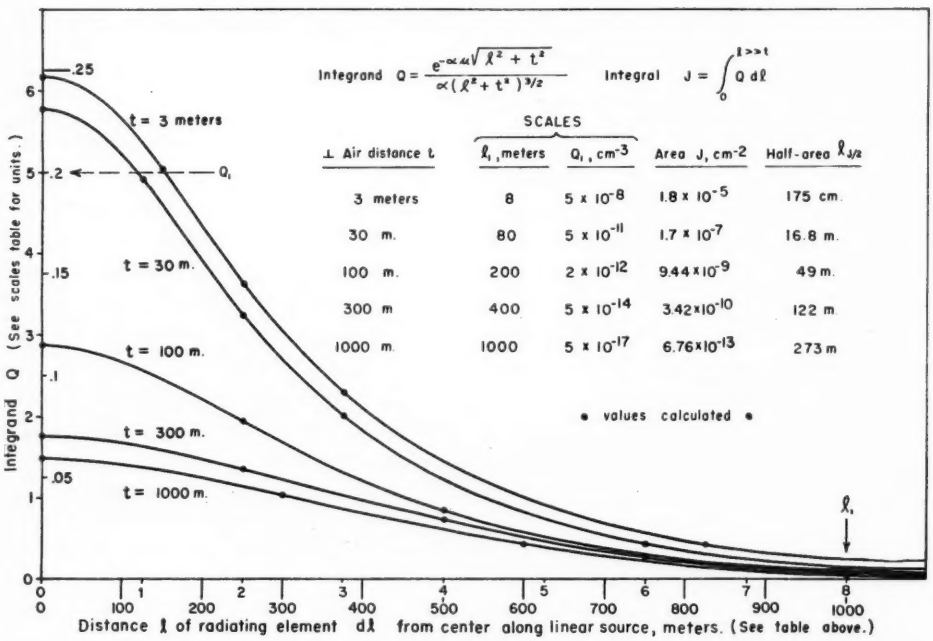
Integrand $Q = \frac{e^{-\alpha\mu\sqrt{l^2+t^2}}}{\alpha(l^2+t^2)^{3/2}}$
Integral $J = \int_0^{l>>t} Q\,dl$
SCALES
⊥ Air distance t | l_1, meters | Q_1, cm^{-3} | Area J, cm^{-2} | Half-area $l_{1/2}$
3 meters | 8 | 5×10^{-8} | 1.8×10^{-5} | 175 cm.
30 m. | 80 | 5×10^{-11} | 1.7×10^{-7} | 16.8 m.
100 m. | 200 | 2×10^{-12} | 9.44×10^{-9} | 49 m.
300 m | 400 | 5×10^{-14} | 3.42×10^{-10} | 122 m
1000 m. | 1000 | 5×10^{-17} | 6.76×10^{-13} | 273 m
• values calculated •
t = 3 meters
t = 30 m.
t = 100 m.
t = 300 m.
t = 1000 m.
.25
.2
.15
.1
.05
Q_1
l_1
Integrand Q (See scales table for units.)
Distance l of radiating element dl from center along linear source, meters. (See table above.)

FIG. 5. Integrations in length for a solid linear source.

of Figure 2. These curves are all to different scales. The areas beneath them are the first integrals of (6) obtained by letting l vary from zero to $l \gg t$. Note that for each value of t, half the area (hence half the radiation) is contributed by segments (dl) of the line source lying within $0 < l < t/2$ of the nearest part, and the more distant segments beyond $l = 2t$ contribute very little of the whole. Thus a profile flown over the center of a line-source of length $2L > 4t_{min} = 4h$ would show the same anomaly as if the length L were practically infinite.

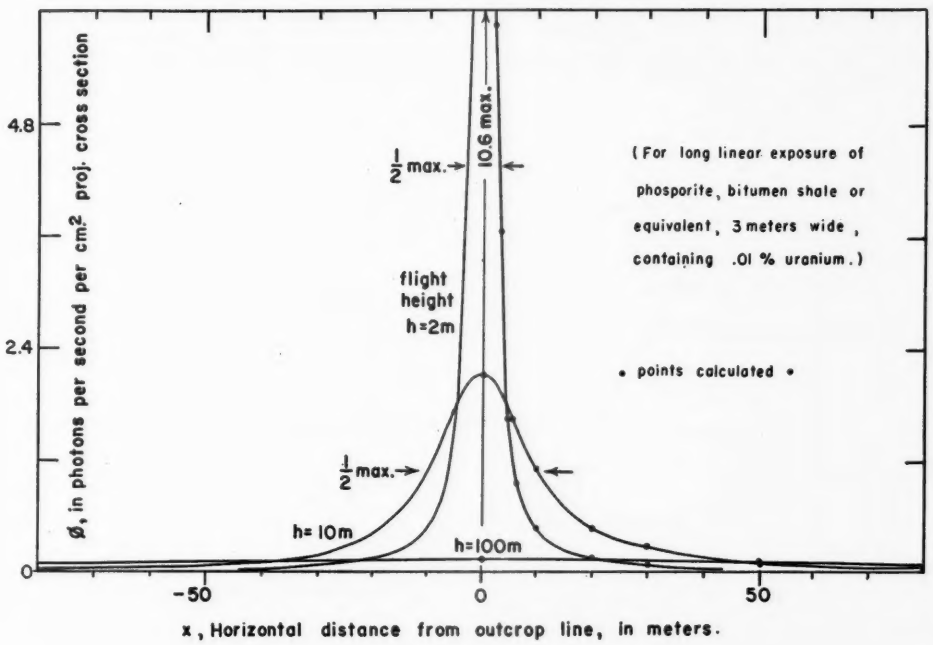

FIG. 6. Computed radiation flux for a long linear source.

Integration in l over the range $-t \ll l \ll t$ involves merely multiplying the areas J under the curves of Figure 5 by two. The resulting values can be well represented by the empirical formula

$$2J = 2/(6{,}640t^2 + 0.195t^4 + 9.36 \times 10^{-7} t^6), \tag{8}$$

where J is in cm^{-2} and t is in meters.

The third integration, in w, can be performed for a narrow linear source by multiplying the coefficients and new integrand, J, by the width W, giving

$$\phi \doteq \frac{cmshW}{2\pi\mu'} J(h, x). \tag{9}$$

This function is plotted *vs.* x for various values of h in Figure 6. The line source

chosen for the example is an outcrop of material such as phosphorite or bituminous shale 300 centimeters wide, of very great length, averaging $c=0.0001$ gm U/gm, a representative value for these types of material. With a source of this shape, the anomaly reaches about half its maximum when the horizontal distance x to the line equals the flying height. The anomaly calculated for a very long linear pitchblende exposure 20 cm wide averaging 10 percent uranium is 67 times as great as that shown in Figure 6 for corresponding flight heights. The peak values of both these examples of line anomalies are plotted *vs* height in Figure 9.

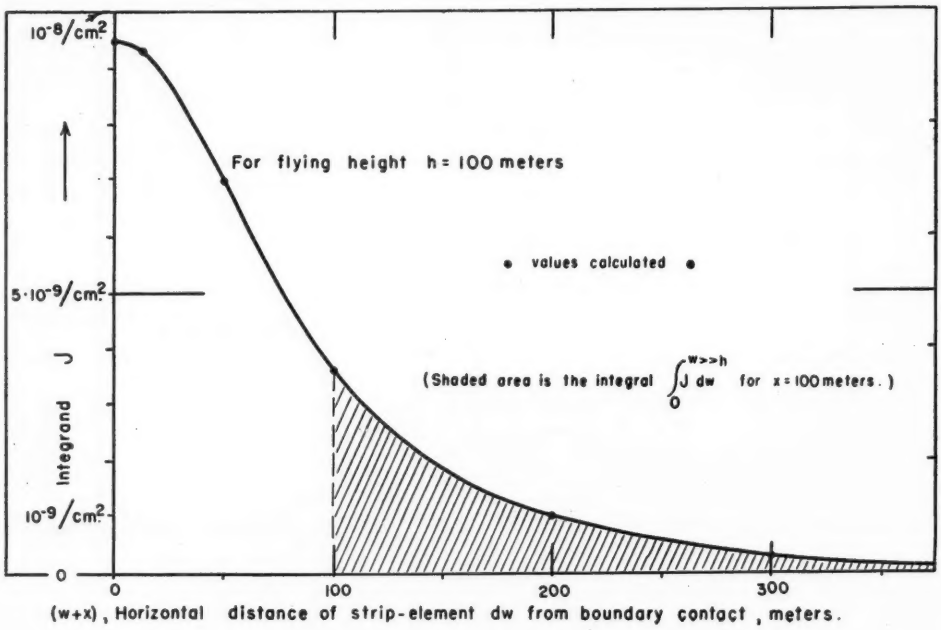

FIG. 7. Integration in width for a solid area source.

A SEMI-INFINITE (HORIZONTAL) PLANE SHEET

By integrating (6) over all values of l as in the previous section, then in w from $w=0$ to $w \gg h$, the effect of approaching a linear contact between two large adjoining surfaces of soil or rock of contrasting radioactivity can be calculated. The last integration is best performed graphically. In Figure 7 values of J from (8) are shown plotted *vs* $(w+x)$ for the particular height $h=100$ meters. Only one curve is drawn, for illustration, because of the extreme differences of scale necessary for other heights. For the case $x=0$, that is, with the detector above the contact line, the integral is the entire area under the curve. For positive values of x, the integration is limited on the left by a boundary at $(w+x)=x$. This reduces the integral due to the radioactive half-plane when the detector is above the adjoining nonradioactive half-plane. For negative values of x, the integral

includes the entire area under the curve, plus that area between $(w+x)=0$ and $(w+x)=x$. When the detector is well over the radioactive half-plane, the integral is just twice that obtained at $x=0$.

The curve of Figure 8 is an example of the anomalies that should be observed in flying across typical geological contacts, e.g., between large exposures of sand, limestone, or basalt and large exposures of shale, clay, or granite. About 70 percent of the total change of intensity is completed in the interval $-h<x<h$. The asymptotic values at each end representing the flux at $h=100$m over large areas, whose soils contain the equivalents of the radium concentrations shown, were

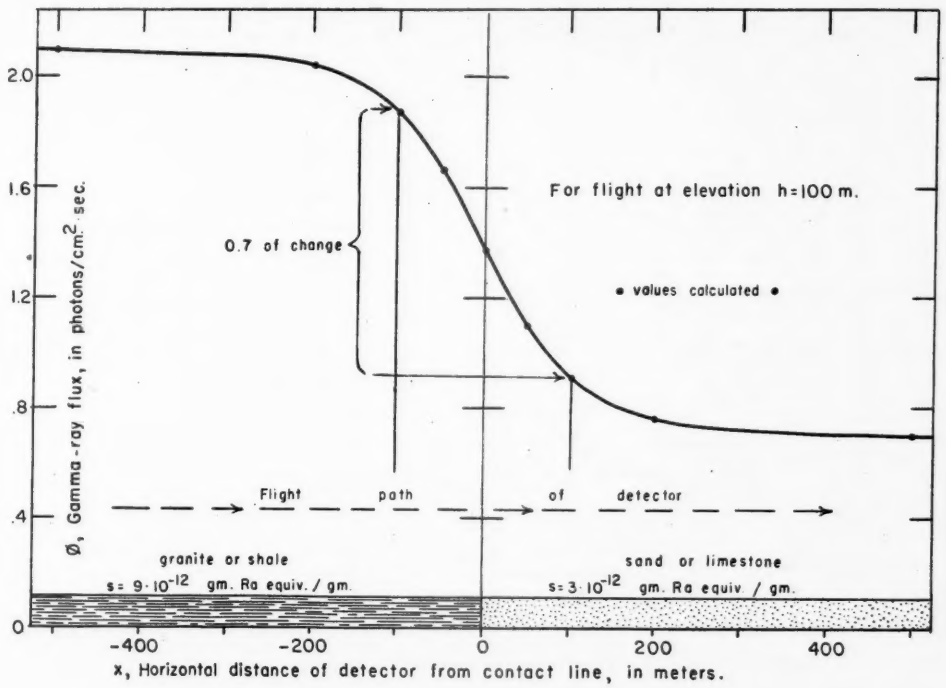

FIG. 8. Computed flux profile over a linear contact.

checked and supplemented by other calculations involving integration of circular areas intercepted by conical surfaces having their apices at the airborne detector. A complete set of calculated flux values are plotted *vs.* height in Figure 9 as "radiation from the ground," whose intensity can generally be expected to be between the two extreme curves shown. For both Figure 8 and Figure 9, the "gamma radiation equivalent" radium concentrations of the rocks named were obtained from Russel (1944).

Figure 9 shows also the flux intensity of cosmic rays as given by Montgomery (1949). This flux is close to 0.025 particle/cm² sec and is normally constant to within a few percent with time and position on the earth's surface. Despite an

increase with altitude of about 20 percent per hundred meters, the cosmic ray component may be considered of negligible importance in airborne prospecting, providing the detector used is about as efficient for gamma rays as for cosmic rays.

EXPERIMENTAL RESULTS

As a supplement to the calculations, a variety of measurements were made in the progress of this investigation. Some of the results will be presented here as of special interest in airborne prospecting.

The apparatus used throughout consisted of an ordinary selfquenching brass

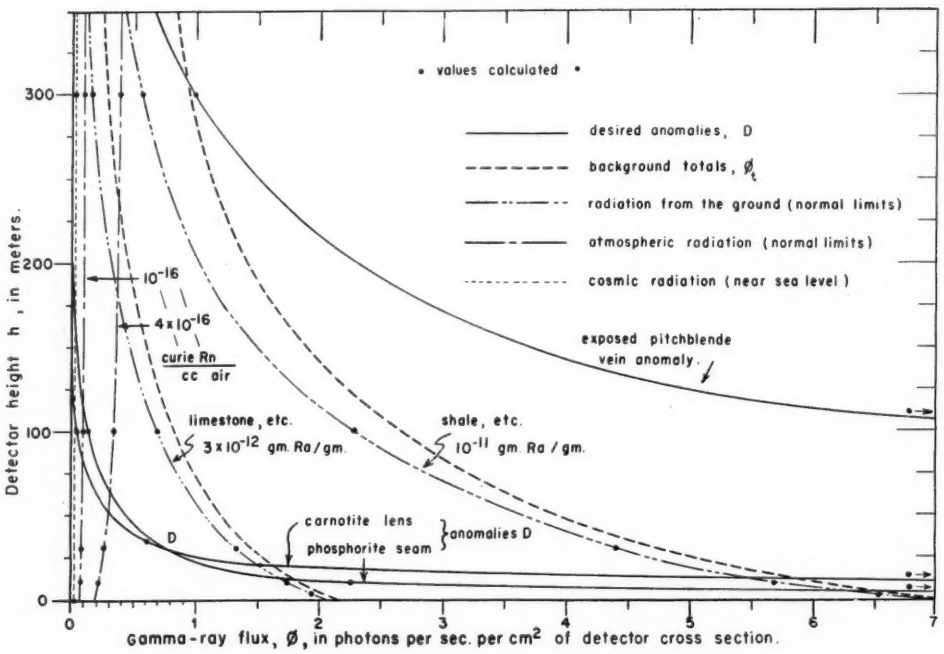

FIG. 9. Computed flux from various sources *vs.* elevation.

geiger-muller counting tube 18 inches long and of one inch diameter, a miniature preamplifier, 500 feet of lightweight, high-voltage twin cable and its reel, and a box containing batteries, a vibrator high-voltage generating circuit with regulator tube, amplifiers, and a mechanical pulse-register. Field-strength counts of five minutes or more, totaling 1,200 pulses or more, were taken at each point in all surveys, insuring a probable error of 2 percent or less for each point. The geiger tube was found upon repeated tests to have a constant sensitivity to radium gamma rays of about 0.0082, despite temperature fluctuations, but to have a cone of insensitivity near the principal axis. It was therefore always used with the axis horizontal, rotating freely at random in a horizontal plane. All

measurements were corrected for pulse-overlap loss occurring in the mechanical register.

The heavy curve of Figure 10 summarizes six vertical profiles of penetrating radiation intensity taken above a large lawn covering thick dolomite-residue soil on the Penn State College campus. They were taken under various weather

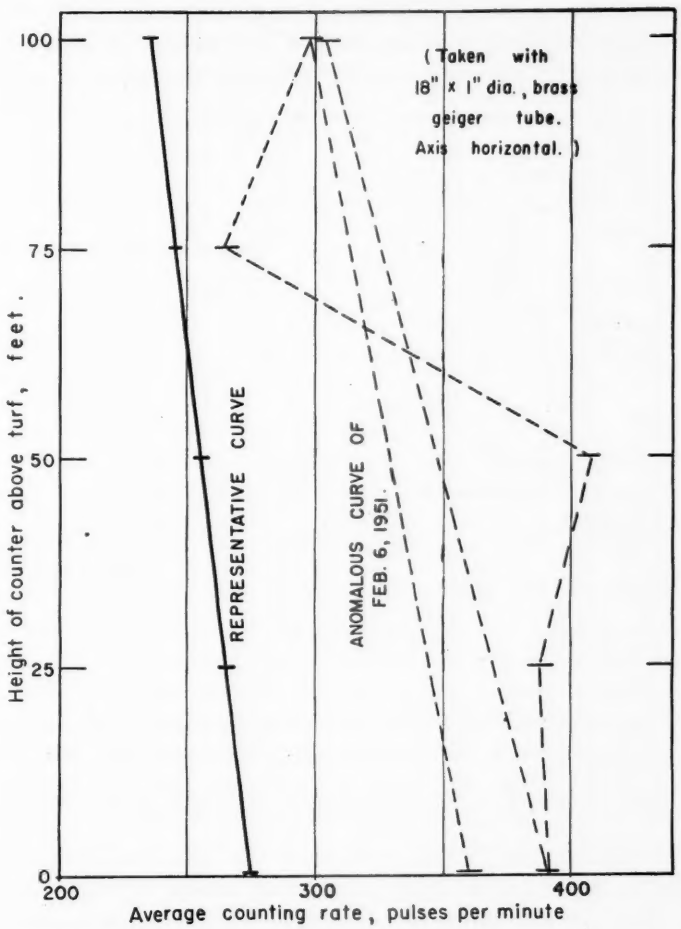

FIG. 10. Measured G.-M. counter elevation profiles over greensward.

conditions by hoisting the geiger tube up one of the flagpoles and staking the rope out away from the pole so as to reduce its shielding effect. The probable errors of the "representative" average curve points are denoted by short horizontal bars. It was found that there is a rather constant vertical gradient in the counting rate of 15 percent per hundred feet. Two locations a half mile apart were found to have identical profiles, to within the probable error, on a given

day. The count rate variation from day to day was never more than ±5 percent at any elevation, except for the "anomalous" curve shown, which was obtained on February 6, 1951, a few days following nuclear bomb tests in Nevada. The day-old snow present at the time, and possibly the air, appear to have been unusually radioactive.

The observed elevation count decrease, divided by the crossection (103 cm^2) and efficiency of the geiger tube, gives a flux gradient of 2.4 flux units per 100 feet, which agrees very well with the slope of the calculated "high" background curve of Figure 9. The x-intercept of this curve is equivalent to 120 counts per

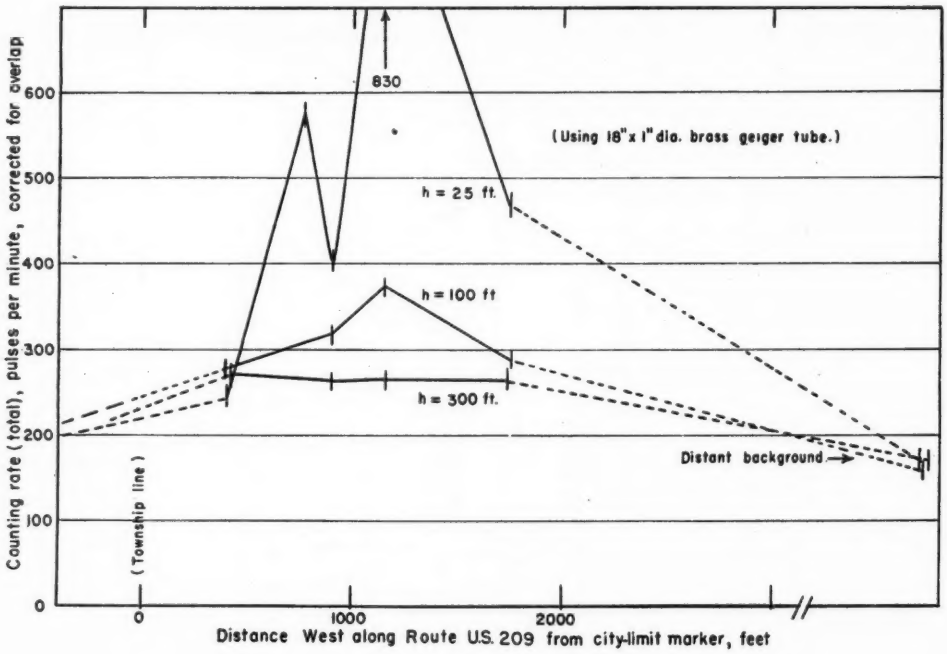

FIG. 11. Measured G.-M. counter profiles over small carnotite exposure.

minute for the geiger tube, so that 157 cpm of the 277 cpm observed background must be due to cosmic rays, which agrees well with a figure of 155 calculated from the cosmic ray flux and tube crossection, assuming 100 percent detection.

Figure 11 shows aerial counting-rate profiles for a small, indefinite, natural carnotite deposit at Mauch Chunk, Pa. These measurements were made by holding the geiger counter, pre-amplifier, and cable aloft on a still day with a Darex J-350 radiosonde balloon holding 110 cubic feet of hydrogen. Stations were established along a road traversing the carnotite exposure, which is near the foot of a 40-degree mountain slope. Small vertical bars in Figure 11 denote probable errors of the measurements. It is evident that this anomaly could be definitely distinguished from the counting error at a flying elevation of 100 feet

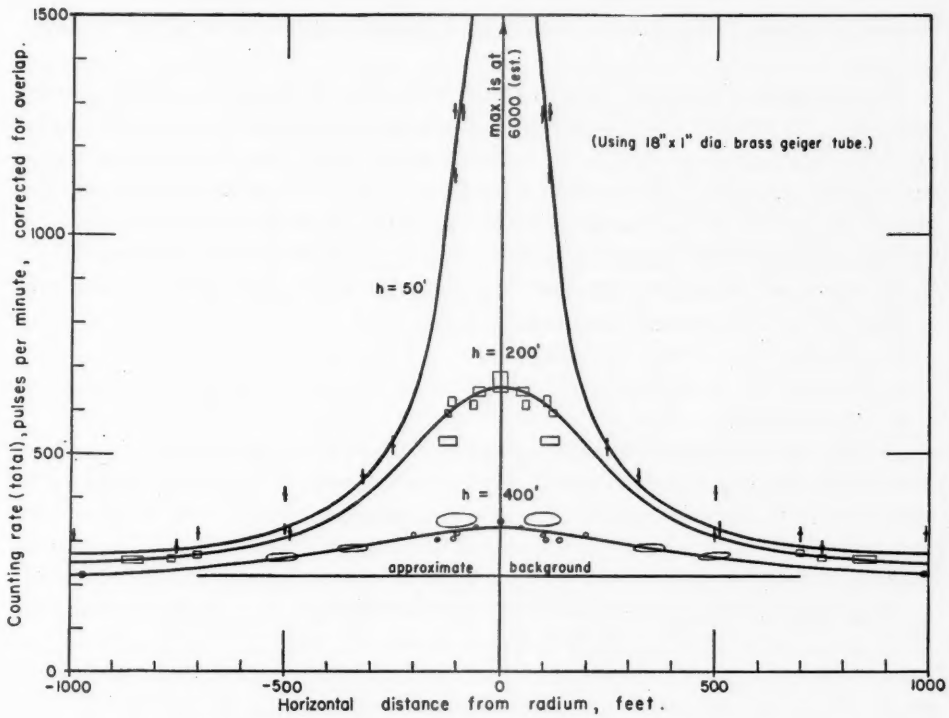

FIG. 12. Measured G.-M. counter profiles over 0.1 Curie of radium.

or less, but not at 300 feet, with the geiger tube used, held by a hovering aircraft for five minutes over each location.

Synthetic anomalies due to 0.1 curie of therapeutic radium are shown in Figure 12. The platinum-encased radium capsules, enclosed in a bottle, were placed upon a level golf course at night, and the balloon-borne counter was flown captive at various positions above it. The bars, rectangles, and ellipses indicate probable errors of counting rate and uncertainties of counter position.

It is noteworthy that the widths of these anomalies at their half-maximum values are approximately $2h$, twice the flying height. This agrees roughly with the calculated profiles of Figure 4, which are $2h$ wide at about 0.3 maximum.

At the larger air distances involved in this experiment, the rate of flux decrease with distance apparently follows the formula of Corner, Day, and Weir (1950). But at distances less than 500 feet from the radium, an excess of radiation is observed, which may be due to the softer rays of radium, for which the mean free path in air is only of the order of 200 feet.

PROFILE "SIGNALS" *vs.* "NOISE"

For the following preliminary analysis of specific surveying problems, the calculated data of Figure 9 will be used, particularly the total background flux

ϕ_t and "anomaly" flux D from a carnotite exposure, as functions of flying height h.

As would be expected, the radiation intensities from large radiating areas decrease slowly with height, due to degradation of the radiation field by the air. Due to geometrical effects, the decrease of the intensities from line sources is much more rapid, and the decrease from sources of small area is more rapid still. Hence a relative gain of amplitude for the anomalies from "point" and line sources over the variations of background due to sources of large area can be had by flying lower. However, the choice of flight elevation must always be a compromise between the conflicting requirements of:

1. Flying high enough for safety.
2. Flying low to increase the relative amplitudes of useful anomalies from ore exposures.
3. Flying high to scan a wider swath of ground in each traverse.

Therefore, amplitude anomalies alone may not always serve as an indicator of ore deposits of average size and grade. But the generally pointed shape of ore anomalies will often be a key characteristic, unless the flight path is such as to prolong and distort them.

The total field intensity is of little interest provided it is constant. However, there are several effects, which cause its observed value to fluctuate from one place to another, that are not connected with radioactive ores. Figures 8 and 9 give an idea of the absolute magnitudes of some of these effects, as discussed below:

1. *Topographic Noise*

The radiation intensity profile taken in passing over an irregular radiating surface will be a smoothed-out image of the surface elevation profile. Approximate corrections can be calculated if desired. Some compensation can be made by flying so as to maintain a nearly constant average distance from the nearest surfaces. The uncorrected residue of "noise" may amount to one third the total. Its amplitude can be estimated roughly for the usual case of linear topographic features (ridges and gullies) as follows:

From Figure 9, the vertical gradient of the flux is about $1/4\ \phi_t$ per 25 meters elevation change Δh. Therefore the uncorrected residue of topographic noise has roughly the amplitude

$$B = 1/3(\phi_t/4)(\Delta h/25m)F, \tag{10}$$

where F is a proper fraction equal to the ratio of the "effective radiating area" of the ridge or depression to the "effective radiating area" of infinite flat terrain for a given height h. This fraction can be measured on Figure 7 for $h=100m$, taking $x=0$, as equal to

$$F = \int_0^{W/2} J\,dw \Big/ \int_0^{w>>h} J\,dw, \tag{11}$$

where W is the width of the strip elevated or depressed by the height Δh. If W is taken equal to 6 (Δh) as a representative case, B can be estimated in terms of Δh using formulas (10) and (11), Figure 7 or its equivalent for other heights h, and values of ϕ_t from table 2. Conversely, the maximum allowable relief Δh over which surveying can be done if the topographic noise amplitude B must not exceed 1/4 the "signal" anomalies D shown in Table 2 can be estimated (graphically), and is shown in Table 2 as a function of surveying height h. In general, flight at elevations below about 25 meters (maximum) elevation should not necessitate any corrections for topography. Flight at greater heights over terrain of relief greater than 10 or 20 meters however may require computation of corrections from a continuous radar altimeter record.

2. *Stratigraphic Noise*

Profiles taken over a series of contacts between contrasting kinds of surface materials will exhibit a series of sigmoid fluctuations like those of Figure 8, with flat portions between. Amplitudes E are given in Table 2. With exposures narrower than $2h$, no flat portion remains and the amplitude is less. Such fluctuations then become difficult to distinguish from ore deposit anomalies by shape or amplitude, except when $h<50$ meters. This case should be rather common in some regions.

3. *Statistical Noise*

The fluctuations in the rate of arrival of photons at a detector are averaged over a period of the order of the "time constant," T, of the measuring equipment. The probable error of any one measurement, by well known statistical principles, is $\pm 0.64\sqrt{N}$ where N is the total number of independent events whose rate of occurrence is averaged. In this case, the momentary probable error is roughly $\pm 0.6\sqrt{CT}$, where $C=\phi_t Ae$ is the gamma-ray "background" counting rate *not including cosmic rays*. A and e are the crossectional area and photon counting efficiency of the detecting apparatus, and ϕ_t is the total gamma-ray flux due to all causes, for which extreme values are given in Figure 9 by heavy dashed lines. In order to insure that the instrument can respond to "signal" anomalies of width $2h$ as the detector is flown along at velocity V, the time constant T must be less than the order of $2h/3V$. Therefore, to keep the probable error (peak-to-peak) amplitude below 1/4 the "signal" amplitudes D, the following approximate condition can be set up

$$1.3\sqrt{\phi_t AeT} \leqq D(AeT/4) \quad \text{or} \quad Ae \geqq (3V\phi_t/2h)(5.2/D)^2. \tag{12}$$

The average physical length of the "statistical humps" in a profile is $VT \leqq 2h/3$ under the above conditions. Hence comes the desirability of keeping their amplitudes lower than those of "signals," since their lengths (VT) are of the same order of magnitude of those due to signals ($2h$), unless T is made excessively short and a still higher detector sensitivity Ae is used.

Table 2 summarizes selected data from Figure 9 and from the above discussion. The assumed safe (helicopter) flying speeds for various elevations were chosen arbitrarily.

TABLE 2

ROUGH SURVEY PLANNING DATA TO DISCOVER AVERAGE CARNOTITE, PHOSPHORITE, ETC., EXPOSURES

h, Meters	Safe V, Meters/sec	ϕ_t	D	E_{max}	Δh for $B=D/4$	T_{max} sec	$(Ae)_{min}$, cm²
		Photons per sec per cm²					
150	50	1.	0.01	1.	8 m	2	135,000
100	35	1.5	0.1	1.5	14 m	1.9	4,200
50	20	2.7	0.4	2.5	18 m	1.7	270
10	10	6.0	2.5	3.7	32 m	0.7	39
3	5	15	10	4.3	50 m	0.4	10.5

Figure 13 shows what can be expected from detecting instruments having various average background counting rates C (not including cosmic rays) at ground level. The statistical-noise criterion alone was utilized here, other effects being assumed negligible. The curves were plotted from a formula obtained from

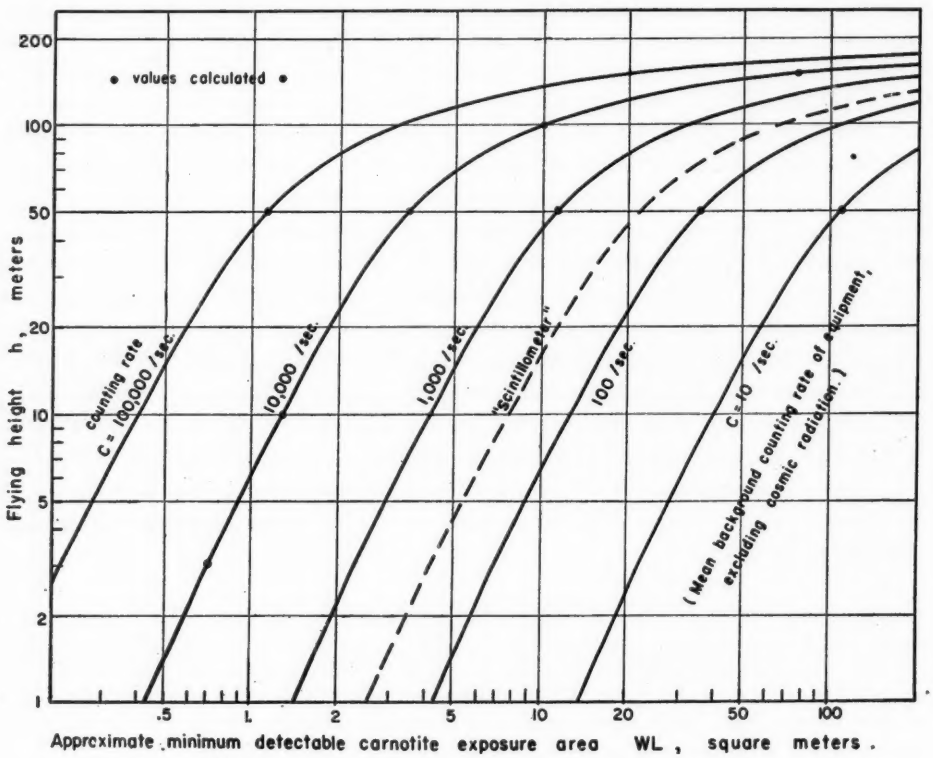

FIG. 13. Estimated probable effectiveness of airborne γ-ray detectors.

(12) by substituting $C = Ae$ (4.5 photons/sec cm^2) and $D = (D_{\text{table 2}})WL/(10 \text{ sq m})$, since the anomaly is proportional to the exposed radiating area WL. The resulting formula is

$$WL = \frac{52 \text{ sq m}}{D_{\text{table 2}}} \left(\frac{\phi_i V (15/\text{sec cm}^2)}{2hC} \right)^{1/2}, \tag{13}$$

where D, ϕ_i, and V are taken from Table 2 as functions of h. The performance of one widely used commercial scintillation detector is predicted by the dashed line at $C = 300$/sec in Figure 13.

The effect of normal time and space variations of atmospheric radon concentration, according to Figure 9, may exceed the desired anomalies D at any elevation above 70 meters. However, Preibsch, Radinger, and Dymak (1937) point out that radon variations may easily exceed the normal range. It is recommended that all surveying be done on sunny or windy days to insure thorough mixing and distribution of the atmospheric radon throughout the survey course. A tie-in loop between beginning and end of each survey would probably be sound practice in order to check up on time-dependent atmospheric changes as well as equipment calibration.

GENERAL RECOMMENDATIONS

To discover the majority of radioactive ore exposures that probably exist, and to distinguish them from spurious interfering effects:

1. The flying height must be as low as possible, considering the rate of area coverage required, the uniformity of terrain, and exposed surface materials of the area. The use of helicopters is recommended.
2. A fast and sensitive detector of the general order of performance shown in Table 2 or Figure 13 is required for proper operation at reasonably fast flying speeds. It should not respond appreciably to cosmic radiation and should be most responsive to gamma radiation from below.
3. Flight should be at constant elevation above the nearest surfaces, or a continuous relative altimeter record should be taken.
4. Flight paths should be across the strike of geological structure lines, to give the sharpest peaked anomalies from possible long linear ore exposures. Spot exposures, conversely, are best distinguished from stratigraphic noise if profiles are flown along the strike. Choice of flight direction depends upon the problem.
5. Flight paths should be spaced no further apart than about twice the flying height to cover an area adequately without undue reduction and broadening of off-course anomalies.
6. Surveys should be done at times of good atmospheric mixing only and when the earth and air are free of synthetic radioactive isotopes.
7. A tie-in loop between beginning and end of each survey is recommended.

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EDITOR'S NOTE: Dr. Cook writes that an official British publication covering some of the same ground as this paper, theoretically and experimentally, has recently been brought to his attention. It is "Aerial Prospecting for Radioactive Minerals," by D. H. Peirson and E. Franklin, Harwell Atomic Energy Laboratory, and it appears in the British *Journal of Applied Physics* Vol. 2 (October 1951), pp. 281–291. The resulting discussion with J. F. Steljes (Nat. Res. Council of Canada) appears in Vol. 3, pp. 203–204 (June 1952), of the same journal.

AN APPLICATION OF PUNCHED CARD METHODS IN GEOPHYSICAL INTERPRETATION*

JOSEPH A. SHARPE† AND PAUL W. FULLERTON‡

ABSTRACT

There is a large class of problems in geophysical interpretation which is solved by the integral over a plane surface of the product of an observed field value or an assumed surface density of some characteristic property F by a weighting function W,

$$S(x, y, z) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} F(u, v, o)W(x - u, y - v, z)dudv.$$

Use of a trigonal coordinate system and substitution of finite sums for the infinite integrals leads to a particularly useful form of adequate practical accuracy, for calculation by punched card methods.

The geophysical interpretation problems to which this attack applies will be listed, and an illustration will be given of the calculation of the second vertical derivative of magnetic total intensity by employment of the widely available I.B.M. punched card machines.

There is a large class of problems in geophysical interpretation which is solved by the integral over a plane surface of the product of an observed field value, or assumed surface density, of some appropriate property of material, F, by a weighting function W.

$$S(x, y, z) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} F(u, v, o)W(x - u, y - v, z)dudv. \qquad (1)$$

In cylindrical coordinates, with origin at (x, y, o),

$$S(x, y, z) = \int_{0}^{2\pi}\int_{0}^{\infty} F(\rho, \theta, o)W(\rho, \theta, z)d\rho d\theta. \qquad (2)$$

For explanation of symbols, refer to Figure 1.

In gravity interpretation, this class of problems includes:

1. Calculation of gravity or torsion balance quantities from assumed or known structure, including terrain.
2. Calculation of torsion balance quantities or deflection of plumb line from gravity map.
3. Calculation of vertical derivatives of gravity.
4. Upward and downward continuations of gravity.

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In magnetics:

1. Calculation of any component of field from assumed or known structure.
2. Calculation of the unmeasured components from the map of any measured component.
3. Calculation of the derivatives of any measured component.
4. Upward and downward continuations of any measured component.

In addition, it includes certain specialized applications in the interpretation of resistivity, self potential, telluric current, and electromagnetic observations.

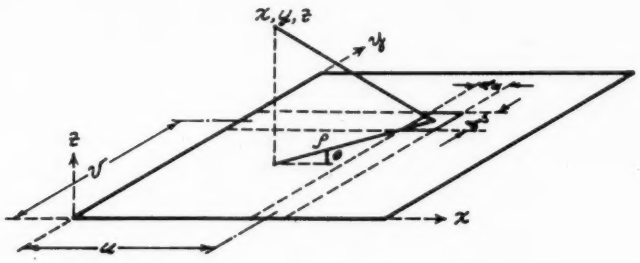

FIG. 1. Coordinate system for formulas (1) and (2).

For numerical calculations of adequate practical accuracy, the infinite surface integral can be replaced by a finite double sum, (3). The trigonal system (Fig. 2) was chosen for this illustration because it lends itself particularly well to the evaluation of this double sum by punched card methods. It has further advantages with regard to uniformity of distribution of initial and final information. Similar procedures may be used with a rectangular grid. The trigonal system will be described first.

$$S(x, y, z) = \sum_{i=0}^{n} \sum_{j=0}^{s} F(\rho_j, \theta_i, 0) W(\rho_j, \theta_i, z). \tag{3}$$

Note that any selected point is surrounded by a series of hexagons with corners at a distance from it of one grid unit, $\sqrt{3}$ grid units, 2 grid units, etc. Coordinates in this system consist of a series of lines parallel to the direction a and separated from each other by a distance $1/2\sqrt{3}$, such as are designated $a_0, a_1, a_2, \cdots a_m \cdots$; and another series of lines parallel to the direction b and separated from each other by a distance $1/2\sqrt{3}$, such as are designated $b_0, b_1, b_2, \cdots b_n \cdots$. Each point on the trigonal grid is designated by a pair of coordinate values of these coordinates, thus the center of the hexagon series shown is at (3, 4).

There are other coordinates which are parallel to the possible radii through a point of the grid and which pass through the corners of hexagons about a given

point, some of which are shown at the point (m, n). These coordinates, which are redundant to the specification of a point, are useful in the punched card evaluation of the double weighted sum. They are determinable from the principal coordinates (a, b) by simple relations as shown by their subscripts, i.e., e_{m+n},

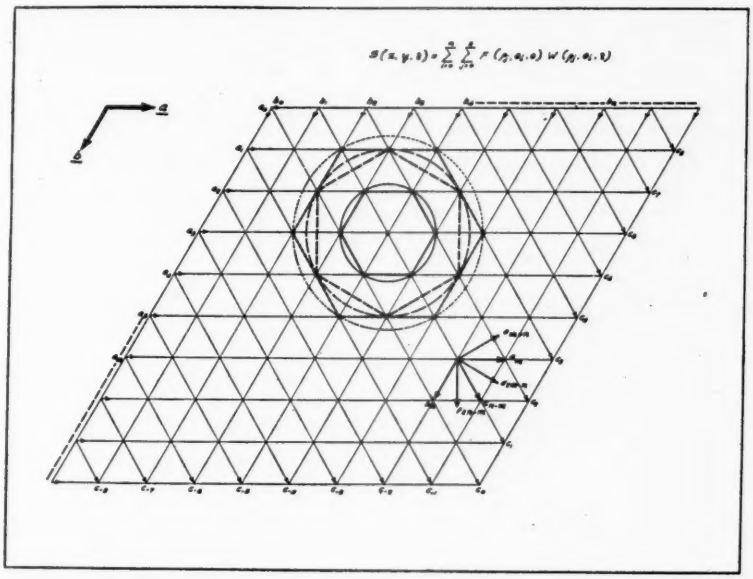

FIG. 2. Trigonal system.

a_m, d_{2m-n}, c_{n-m}, f_{2n-m}, b_n. Note that coordinate lines parallel to the c direction will be separated by a distance of $1/2\sqrt{3}$ grid units, but that those parallel to the d, e, and f directions will be separated by a $1/2$ grid unit.

It has been shown by Peters that one can obtain vertical derivatives of this class of surface integral problems. We will include in this illustration the calculation of the second vertical derivative of total magnetic intensity.

We will first wish to determine the coefficients of the least squares parabola passing through the points on the circles selected for our system.

$$\overline{F}(r) = a_0 + a_2 r^2 + a_4 r^4 \tag{4}$$

using circles of radii:

$$r_1 = 1,$$

$$r_2 = \sqrt{3},$$

$$r_3 = 2.$$

In deriving weight factors for this case, we will assume circular symmetry;

$$\frac{\partial F}{\partial \theta} = 0$$

Then the Laplace equation in cylindrical coordinates takes the form:

$$\frac{\partial^2 F}{\partial z^2} = -\left[\frac{\partial^2 F}{\partial r^2} + \frac{1}{r}\frac{\partial F}{\partial r}\right].$$

Assuming a least squares parabola through the points $\overline{F}(o)$, $\overline{F}(r_1)$, $\overline{F}(r_2)$, $\overline{F}(r_3)$ of the form above, we obtain on differentiating eq. (4) and substituting:

$$\left.\frac{\partial^2 F}{\partial z^2}\right|_{0,0,0} = -\left[\frac{1}{r}\frac{\partial F}{\partial r} + \frac{\partial^2 F}{\partial r^2}\right] = -4a_2.$$

Our problem then is to find the a_2 of the least squares parabola $a_0+a_2r^2+a_4r^4$.[1] Setting:

$$\sum [\{\overline{F}(0) - a_0\}^2 + \{\overline{F}(1) - (a_0 + a_2 + a_4)\}^2 + \{\overline{F}\sqrt{3} - (a_0 + 3a_2 + 9a_4)\}^2 + \{\overline{F}(2) - (a_0 + 4a_2 + 16a_4)\}^2] = \min,$$

$$\frac{\partial \sum}{\partial a_0} = \overline{F}(0) - a_0 + \overline{F}(1) - (a_0 + a_2 + a_4) + \overline{F}\sqrt{3} - (a_0 + 3a_2 + 9a_4) + \overline{F}(2) - (a_0 + 4a_2 + 16a_4) = 0,$$

or

$$4a_0 + 8a_2 + 26a_4 = \overline{F}(0) + \overline{F}(1) + \overline{F}\sqrt{3} + \overline{F}(2),$$

$$\frac{\partial \sum}{\partial a_2} = \overline{F}(1) - (a_0 + a_2 + a_4) + 3\{\overline{F}(\sqrt{3}) - (a_0 + 3a_2 + 9a_4) + 4\{\overline{F}(2) - (a_0 + 4a_2 + 16a_4)\} = 0,$$

or

$$8a_0 + 26a_2 + 92a_4 = \overline{F}(1) + 3\overline{F}\sqrt{3} + 4\overline{F}(2),$$

$$\frac{\partial \sum}{\partial a_4} = \overline{F}(1) - (a_0 + a_2 + a_4) + 9\{\overline{F}(\sqrt{3}) - (a_0 + 3a_2 + 9a_4)\} + 16\{\overline{F}(2) - (a_0 + 4a_2 + 16a_4)\} = 0$$

[1] Refer Leo S. Peters, "The Direct Approach to Magnetic Interpretation and Its Practical Application," *Geophysics*, XIV, No. 3 (1949), 290–320, for the derivation of these equations.

or

$$26a_0 + 92a_2 + 338a_4 = \overline{F}(1) + 9\overline{F}(\sqrt{3}) + 16\overline{F}(2).$$

We now have to solve the following:

$$\begin{aligned} 4a_0 + 8a_2 + 26a_4 &= F(0) + F(1) + F(\sqrt{3}) + F(2) \\ 8a_0 + 26a_2 + 92a_4 &= F(1) + 3F(\sqrt{3}) + 4F(2) \\ 26a_0 + 92a_2 + 338a_4 &= F(1) + 9F(\sqrt{3}) + 16F(2); \end{aligned}$$

$$\text{Let } \Delta = \begin{vmatrix} 4 & 8 & 26 \\ 8 & 26 & 92 \\ 26 & 92 & 338 \end{vmatrix} = 8 \begin{vmatrix} 2 & 4 & 13 \\ 4 & 13 & 46 \\ 13 & 46 & 169 \end{vmatrix}$$

$$= 8 \times 2 \begin{vmatrix} 13 & 46 \\ 46 & 169 \end{vmatrix} - 8 \times 4 \begin{vmatrix} 4 & 46 \\ 13 & 169 \end{vmatrix} + 8 \times 13 \begin{vmatrix} 4 & 13 \\ 13 & 46 \end{vmatrix}$$

$$= 16[81] - 32[78] + 104[15] = 360,$$

$$\Delta a_2 = \begin{vmatrix} 4 & F(0) + F(1) + F(\sqrt{3}) + F(2) & 26 \\ 8 & F(1) + 3F(\sqrt{3}) + 21F(2) & 92 \\ 26 & F(1) + 9F(\sqrt{3}) + 16F(2) & 338 \end{vmatrix},$$

$$= -\{F(0) + F(1) + F(\sqrt{3}) + F(2)\} \begin{vmatrix} 8 & 92 \\ 26 & 338 \end{vmatrix}$$

$$+ \{F(1) + 3F(\sqrt{3}) + 4F(2)\} \begin{vmatrix} 4 & 26 \\ 26 & 338 \end{vmatrix}$$

$$- \{F(1) + 9F(\sqrt{3}) + 16F(2)\} \begin{vmatrix} 4 & 26 \\ 8 & 92 \end{vmatrix},$$

$$= -312F(0) + \{676 - 312 - 160\}F(1) + \{2028 - 312 - 1440\}F(\sqrt{3})$$
$$+ \{2704 - 312 - 2560\}F(2)$$
$$= -312F(0) + 204F(1) + 276F(\sqrt{3}) - 168F(2);$$

$$a_2 = -0.86667F(0) + 0.56667F(1) + 0.76667F(\sqrt{3} - 0.46667F(2),$$

$$\frac{\partial^2 F}{\partial z^2} = -4a_2 = 3.46667F(0) - 2.26667\overline{F}(1) - 3.06667\overline{F}(\sqrt{3}) + 1.86667\overline{F}(2).$$

Thus, for our case

$$\frac{\partial^2 F}{\partial z^2} = 3.4667F(0) - \sum_1^6 0.37778F_i(1) - \sum_1^6 0.51111F_i(\sqrt{3}) + \sum_1^6 0.31111F_i(2).$$

Obtaining a_2 at any point now resolves itself into a process of adding to the weighted field value, at the point, the sum of the products of the field values and their respective weight factors for each of the corners of the hexagons associated with this point. Such a sum must be obtained for every point on the grid.

The first step is to superimpose a trigonal grid of proper choice of grid unit over the contoured map representing the data to be operated on, to interpolate

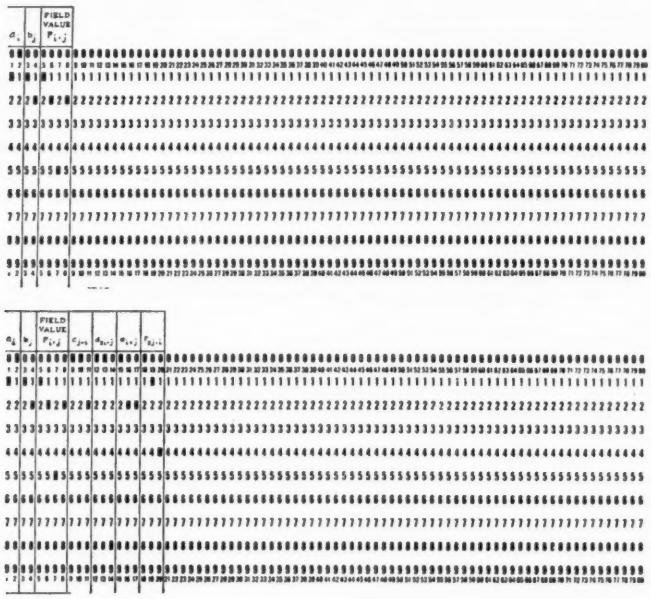

FIG. 3. Upper—Card punched for each grid point. Lower—Card with computed coordinates.

the field value at each grid point, and to tabulate the coordinates of each grid point and the associated field value.

In order to convert the given data into form for processing, it is necessary to perform a clerical operation of key punching the tabulated information into punched card form. One card is punched for each grid point. This card will contain identifying coordinate information along with the field value. To eliminate transcription errors, the cards are each verified against the original tabulation. For this operation, the cards are kept in the same order as they were punched from the tabulation. But in verification, instead of punching, the machine merely checks for the presence or absence of the correct numbers and signals any errors.

With the coordinates a and b as in the upper card (Fig. 3), the necessary redundant coordinates are computed in one pass through the calculator and punched into the card, as in the lower card (Fig. 3).

Either the electronic Model 604 Calculating Punch or the electro-mechanical

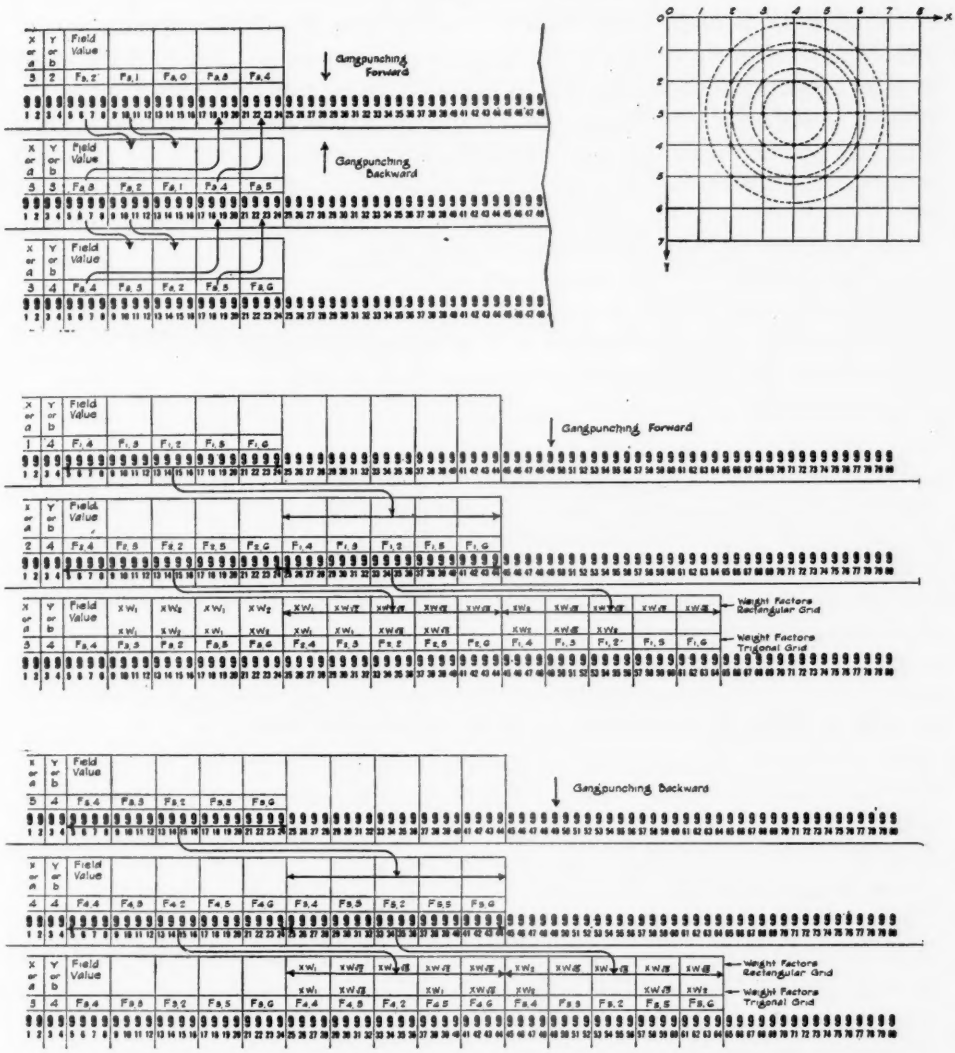

FIG. 4. Offset gang punching procedure.

Model 602A can be utilized in this and the following operations. These machines have storage registers where factors read from the punched card can be stored either in vacuum tube trigger circuits (604) or electro-mechanical-relay circuits (602A). Factors in storage can then be operated upon during the calculate cycle of the machine by the wiring of a control panel.

As illustrated (Fig. 2), the values on the unit radius about a point p, all to be associated with particular weight factor, w_1, and those values on the radius of

two units to be associated with another weight factor W_2, will lie on the a, b, and c coordinates. The operations along these coordinates are identical and are wired as a set sequence. To process, the cards are first sorted into ascending sequence, using a coordinate intersecting the coordinate of process, then into ascending sequence by the coordinate of process. Processing in the a direction, this would mean sorting first on b, then on a. The machine operations along a, b, or c consist of:

1. Reading the field value from the card, $F_{i,j}$.
2. Multiplying the field value times weighting factor W_1.
3. Storing this product $F_{i,j}W_1$.
4. Multiplying the previous product $(F_{i,j-2}W_1)$ by W_2/W_1 to obtain $F_{i,j-2}W_2$, the correctly weighted value for the i,j center point.
5. Summing this product (4) and the stored $W_1F_{i,j-1}$ product and punching this sum into the i,j card.

Thus, three cards along any row or diagonal must be fed before a partial answer is available. The pattern is consistent. After three cards are fed, the values $F_{i,j-2}(W_2)+F_{i,j-1}(W_1)$ are available for punching into the i,j card. On the fourth card, the stored $F_{i,j-1}(W_1)$ value is multiplied by a stored factor W_2/W_1, and combined with the stored $F_{i,j}W_1$ so that the value of $F_{i,j-1}(W_2)+F_{i,j}(W_1)$ is available for punching into the i,j card.

The procedure is carried through until all cards have been processed. Then, by placing the cards in the feed backwards, the same operation permits the $F_{i,j-2}W_1+F_{i,j1}W_2$ value to be punched into the $F_{i,j}$ card. In the case where circular symmetry of the weighting factors does not exist, it is a simple matter to introduce new weighting factors W_1^1 and W_2^1/W^1 into storage for this run. Also, on this run backwards, the forward partial answer $(F_{i,j-1}W_1+F_{i,j-2}W_2)$ is read from the card and included so that completion of the run provides the complete row or diagonal partial answer.

One great advantage of the machine procedure is a positive check on the accuracy of the operations. At the completion of each pass along a coordinate direction the weighting can be rapidly checked on the accounting machine. This is done by accumulating the sum of the individual field values and the partial answers $V_{i,j}$ obtained on each of these passes.

Check on a, b, c weighted sums:

$$\sum_{0}^{n,s} V_{i,j}{}^{a} = [W_1 + W_2]\left[2\sum_{0}^{n,s} F_{i,j} - (F_{0,0} - F_{n,s})\right] - W_2[F_{0,1} + F_{n,s-1}]$$

$$\sum_{0}^{n,s} V_{i,j}{}^{b} = [W_1 + W_2]\left[2\sum_{0}^{n,s} F_{i,j} - (F_{0,0} + F_{n,s})\right] - W_2[F_{1,0} + F_{n-1,s}]$$

$$\sum_{0}^{n,s} V_{i,j}{}^{c} = [W_1 + W_2]\left[2\sum_{0}^{n,s} F_{i,j} - (F_{n,0} + F_{0,n})\right] - W_2[F_{n-1,0} + F_{0,n-1}].$$

Check on *d, e, f:*

$$\sum_{0}^{n,s} V_{i,j}{}^{d} = W\sqrt{3}\left[2\sum_{0}^{n,s} F_{ij} - (F_{n,0} + F_{n,1})\right]$$

$$\sum_{0}^{n,s} V_{i,j}{}^{e} = W\sqrt{3}\left[2\sum_{0}^{n,s} F_{ij} - (F_{n,s} + F_{n,s-1})\right]$$

$$\sum_{0}^{n,s} V_{i,j}{}^{f} = W\sqrt{3}\left[2\sum_{0}^{n,s} F_{i,j} - (F_{0,n} + {}_{1,n})\right]$$

Check on final summation:

$$\sum_{0}^{n,s} \frac{\partial^2 F_{i,j}}{\partial z^2} = W_0\left[\sum_{0}^{n,s} F_{i,j}\right] + \sum_{0}^{n,s} V_{i,j}{}^{a} + \sum_{0}^{n,s} V_{i,j}{}^{b} + \sum_{0}^{n,s} V_{i,j}{}^{c} + \sum_{0}^{n,s} V_{i,j}{}^{d} + \sum_{0}^{n,s} V_{i,j}{}^{e} + \sum_{0}^{n,s} V_{i,j}{}^{f}$$

A slightly different sequence of operations is wired for processing on the *e, f,* and *g* coordinates. The selection between these operations is made by the machine on the basis of a code punch entered into the cards on the final *c* calculation. In this operation, the $F_{i-2,j}W\sqrt{3}+F_{i,j}W\sqrt{3}$ value is punched into the $F_{i,j}$ card in one run in the forward direction. Then, on the reproducing punch, this sum, which represents the contributions to the $F_{i-1,j}$ center point, is transferred to the $F_{i-1,j}$ card by feeding the cards backwards.

Thus, by succession of sorts and passes through the calculating punch, the cards are ordered by *a, b, c, d, e,* and *f,* and the correct weight factors are applied to the neighboring points. In each case, the partial solution, consisting of the one or two adjoining values along the axis of process times their weight factors, are punched into the card. On the final pass through the calculator, these partial answers are summed into the desired answer.

The above procedure is directed toward the 604 Electronic Calculating Punch where no loss in the 100 card/minute speed is caused by multiplication and division. In using the 602A calculating punch where these operations appreciably affect the time, the procedure can be modified so that the associated points can be accumulated in one card on the reproducing punch at 100 cards/minute, then summed and weighted on the 602A with only one multiplication for each weight factor involved. This modification has some advantages in working with a rectangular system with either calculating punch. The reproducing punch has the ability to punch information from a lead card into cards following. As in the previous procedure, cards are ordered by coordinate direction on the sorter. Then, by passing the cards through the reproducing punch, one or more of the adjoining field values along the axes of process can be punched into each card. Processing in reverse adds the values on the other side. In an operation where a

"residual" is computed, this process may be employed. Then, depending upon the relationship between the grid interval and the residual pattern, one, two, or more of the intermediate values can be ignored when summing.

The rectangular grid system is shown (Fig. 4) along with diagrams indicating the manner of accumulating the associated field values in each card. As the values are gang punched, a positive check on the accuracy of the operation is possible through the use of the comparing magnets in the reproducing feed. By compari-

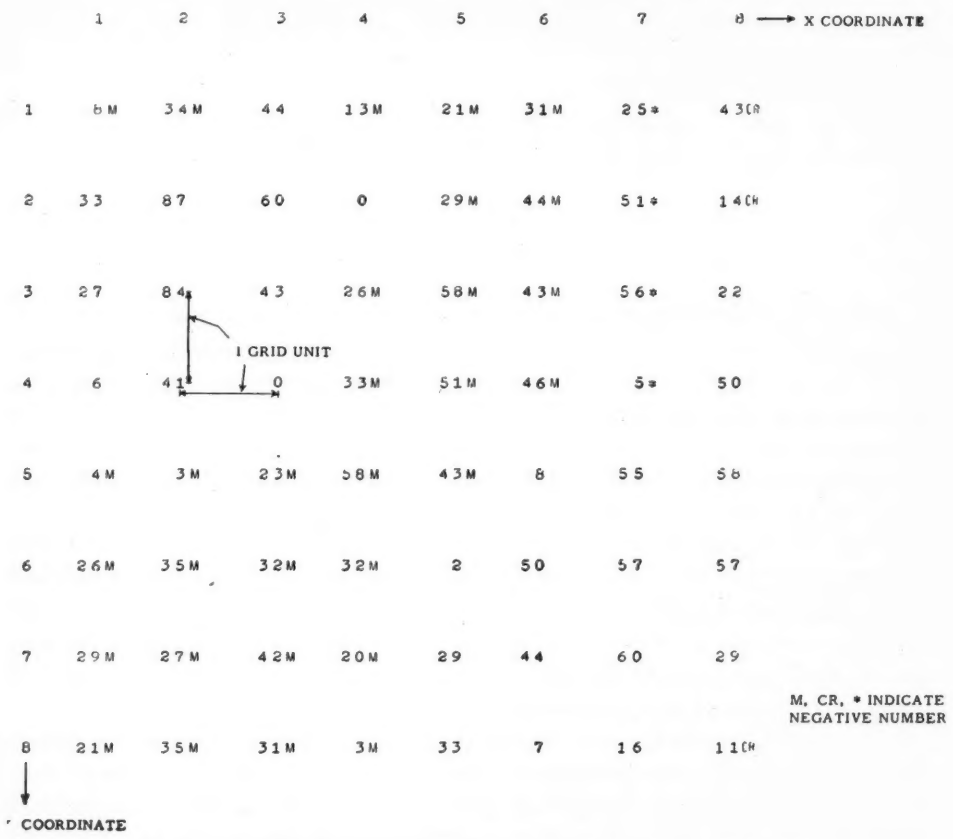

FIG. 5. 2nd derivatives posted by accounting machine on rectangular grid.

son with the trigonal system (Fig. 2), note that this procedure is amenable to both. If fewer circles are desired, the only changes necessary are in the gang punching operation and the weighting step on the calculating punch.

The steps in this procedure are (where a and b are the trigonal and x and y are the rectangular coordinates):

1. Key punch and verify X or (a), y or (b) coordinates and the field value $F_{i,j}$.

2. Sort into order by y or (b) then X or (a). Check the final arrangement by a sequence check on the collator.
3. Gang punch forward, then placing cards in feed upside down and in reverse order, gang punch backwards. This places $F_{3,3}F_{3,2}$ into $F_{3,4}$ and then $F_{3,5}F_{3,6}$, into $F_{3,4}$. Similarly $F_{2,3}F_{2,2}$ into $F_{2,4}$ with $F_{2,5}$ and $F_{2,6}$.
4. Sort by y or (b). Sequence check.
5. Gang punch forward. This places $F_{1,4}$ and values associated with it (i.e., $F_{1,2}$; $F_{1,3}$;$F_{1,5}$; $F_{1,6}$) into $F_{3,4}$ card. Similarly, placing $F_{2,4}$ and its associated values into $F_{3,4}$ card.
6. Reproduce backward at the same time gang punching backward. Reproduce only the values associated with a particular point (i.e., $F_{3,2}$; $F_{3,3}$; $F_{3,5}$; $F_{3,6}$ associated with $F_{3,4}$). This will place the $F_{5,4}$ and $F_{4,4}$ values and their associated values into the $F_{3,4}$ card of the reproduced deck (Deck 2).
7. On calculating punch, crossfoot values of equal radii and apply weighting factors. This is done on both deck 1 and deck 2, punching the partial sums in each case in the same field.
8. Collate deck 1 with deck 2.
9. Tabulate values on the accounting machine, controlling on point to obtain final sum of the two cards for each point.
10. On two runs through the accounting machine, accumulate the individual card fields for check on multiplier. The sum of the final answers must agree with the sum of the values in each card field, each multiplied by its respective weight factor. The sum of each field is available from these runs on the accounting machine. The weight factors are applied to the 19 (trigonal grid) or 25 (rectangular grid) sums manually.

By referring to the trigonal system (Fig. 2) and the rectangular system (Fig. 4), it is apparent that additional circles can be included. For instance, using the first method, hexagons whose points lie on the coordinates a, b, c, can be added in the same pass as the two hexagons indicated, similarly with those whose points lie on d, e, f. Hexagons on the other radii through the point must be added in separate passes, using additional coordinate directions g, h, i, etc.

Adding more circles in the second method requires that the gang punching operation be extended along with additional reproducing. This will produce four (or more) cards per point contrasted with the two cards in the example.

Although at first glance the procedure seems to include quite a few steps, experience shows that elapsed processing time, including key punching and listing final answers, averages out at less than 2/3 minute per point on the 602A and 1/4 minute per point on the 604. (See Fig. 6.) The wide availability of these machines plus the speed and accuracy made it appear that this approach might offer some benefit to others engaged in this type of work.

As an illustration, we have used punched card methods to prepare from a

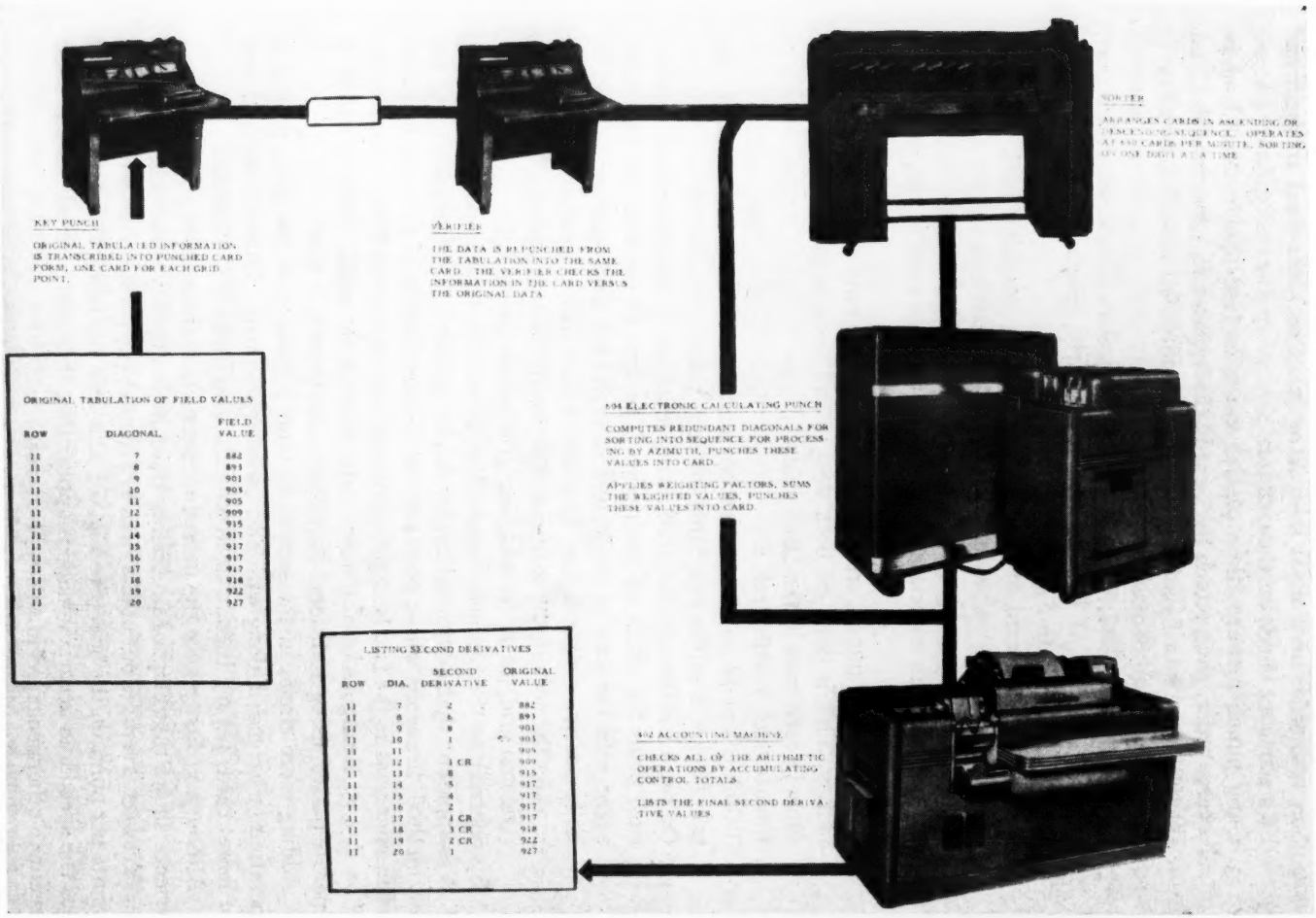
KEY PUNCH
ORIGINAL TABULATED INFORMATION IS TRANSCRIBED INTO PUNCHED CARD FORM, ONE CARD FOR EACH GRID POINT.
VERIFIER
THE DATA IS RE-PUNCHED FROM THE TABULATION INTO THE SAME CARD. THE VERIFIER CHECKS THE INFORMATION IN THE CARD VERSUS THE ORIGINAL DATA
SORTER
ARRANGES CARDS IN ASCENDING OR DESCENDING SEQUENCE. OPERATES AT 450 CARDS PER MINUTE. SORTING ON ONE DIGIT AT A TIME
ORIGINAL TABULATION OF FIELD VALUES
ROW DIAGONAL FIELD VALUE
11 7 882
11 8 893
11 9 901
11 10 905
11 11 905
11 12 909
11 13 915
11 14 917
11 15 917
11 16 917
11 17 917
11 18 918
11 19 922
11 20 927
604 ELECTRONIC CALCULATING PUNCH
COMPUTES REDUNDANT DIAGONALS FOR SORTING INTO SEQUENCE FOR PROCESSING BY AZIMUTH, PUNCHES THESE VALUES INTO CARD.
APPLIES WEIGHTING FACTORS, SUMS THE WEIGHTED VALUES, PUNCHES THESE VALUES INTO CARD.
LISTING SECOND DERIVATIVES
ROW DIA. SECOND DERIVATIVE ORIGINAL VALUE
11 7 2 882
11 8 6 893
11 9 8 901
11 10 1 905
11 11 905
11 12 1 CR 909
11 13 6 915
11 14 5 917
11 15 4 917
11 16 2 917
11 17 1 CR 917
11 18 3 CR 918
11 19 2 CR 922
11 20 1 927
602 ACCOUNTING MACHINE
CHECKS ALL OF THE ARITHMETIC OPERATIONS BY ACCUMULATING CONTROL TOTALS.
LISTS THE FINAL SECOND DERIVATIVE VALUES.

FIG. 6. Sequence of operations on I.B.M. machines.

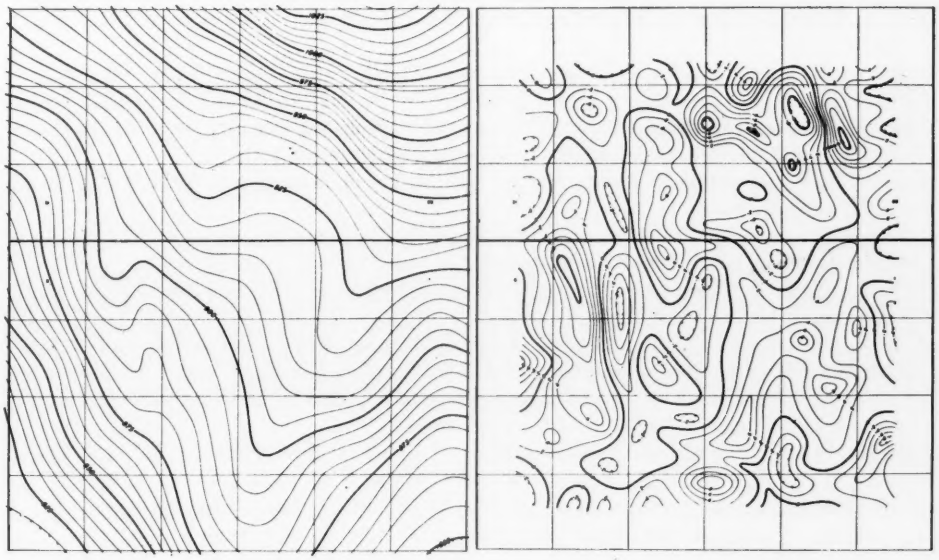

FIG. 7. Computed second vertical derivative for a small area in Osage County, Oklahoma. Squares are sections, or square miles.

map of the total intensity of the magnetic field over a small area in Osage County, Oklahoma, a map of the second vertical derivative of the total intensity (Fig. 7). Due to the thin sedimentary section existing in this area, observation lines were one-half mile apart. The contour interval employed for the total intensity map was 5 gammas.

Due to the small lateral extent of anomalies on the total intensity map, a grid unit of one-quarter mile was used. The resulting second derivatives were contoured at an interval of 2 gammas/(grid unit).[2]

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FREQUENCY ANALYSIS OF SEISMIC WAVES*

J. JAY JAKOSKY† AND JOHN J. JAKOSKY, JR.‡

ABSTRACT

This paper contains a brief description of the general factors governing choice of recording media; a description of the instrumentation employed in wave analysis studies; a review of some of the factors involved in the generation of seismic waves and their propagation; and a few examples of wave separation to illustrate some of the points discussed and their application to seismic exploration.

The results of these studies demonstrate that instrumentation of this type is of advantage in those areas where frequency discrimination can improve the signal/interference ratio.

INTRODUCTION

Starting in 1947 our company has been conducting studies of the frequency components in reflected and refracted seismic waves. This work has been done chiefly in Oklahoma, Texas, Kansas, New Mexico, Alabama, Louisiana, and California, and in two Provinces of Canada. The work in the United States has been conducted chiefly in connection with research projects with the Continental Oil Company and the Signal Oil and Gas Company. A major portion of the work in Canada was conducted under a joint project with the Tidewater Associated Oil Company, as operator, and the Ohio Oil Company, Columbia Carbon Company, and Atlantic Refining Company. Acknowledgment is made of the fine cooperation extended by those organizations.

RECORDING AND REPRODUCING EQUIPMENT

The different components in the seismic wave are most conveniently studied by first recording the seismic wave energy on some reproducible media and then repetitively "playing-back" this recording as the various circuit parameters are changed to accentuate the desired components under study.

The general idea of recording upon a reproducible media has been proposed by numerous investigators during the past decade. For our early investigations, various types of sound recording and reproducing equipment were employed. These were chiefly of the so-called "phonographic" type which included wire and tape magnetic recording, and variable area and variable density photographic film recording. It was found that practically any of the recognized systems for recording and reproducing sonic energy may be employed in seismic operations, the final choice being governed largely by personal preference and the type of

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operations to be conducted. Magnetic recording has an obvious advantage in not requiring the processing of photographic films but suffers from the disadvantages introduced by much more complicated, costly, and bulky equipment. The magnetic recorder and its associated power supply weighed more than the complete seismic equipment to which it was connected, whereas the complete photographic recorder did not add more than 30 pounds to the conventional seismic equipment.

Generally the magnetic recording gave a signal/noise ratio of about 40 db, as compared to about 35 db for the photographic recording. However, this superiority of about 5 db was seldom realized because the greater noise present in photographic recording lies a number of octaves above the seismic frequencies. Therefore when normal filtering was employed for the seismic band the net signal/noise ratio became practically the same for either the magnetic or the photographic systems.

Since the chief objective of our work was to simplify the field procedure and equipment our choice was for photographic recording. As our investigations progressed it became evident also that, from our operational viewpoint, direct oscillographic recording, as compared to variable area or variable density recording, had certain advantages for seismic investigations: i.e., (1) the entire background and experience heritage of both the geologist and the geophysicist is built upon the interpretation of oscillographic-type records, and (2) much of the preliminary computing involving first arrivals, uphole time, weathering, etc., could be made directly from the oscillographic record without the necessity of first playing-back the recording, which often facilitated computing and speeded up the resultant interpretation.

From an instrumental viewpoint, it is necessary that the electronic recording and reproducing equipment not only operate with high fidelity, but in addition, have stable characteristics as regards gain and phase-shift in order to allow quantitative measurements to be made. Also, the complimentary film transport mechanisms in both the recorder and the reproducer must move the recording film at synchronous speed and with strict limitations on flutter and "wow" to maintain a time accuracy of plus or minus one millisecond.

From an operational viewpoint, the object is to make a single broad-band recording in the field, and then by playing-back this broad-band recording later, to make as many different records as there are desired filtering or mixing combinations. The desired number will of course depend upon the area and the end use of the data.

Figure 1 is a schematic diagram of the complete instrumentation. Each seismometer, or nest of seismometers, is recorded through its own amplifier, on a separate trace. As will be seen from the diagram, the recording truck embodies *dual* recording. The *conventional* seismic recording system may employ any desired mixing and filtering when making the usual paper record. The paper record, from the conventional camera, is developed after each shot, and is im-

mediately available for inspection. In parallel with the conventional system is a special oscillograph for recording the broad-band, reproducible records. After the initial adjustments have been made, the broad-band oscillograph camera is controlled by a relay actuated by the motor switch on the conventional paper camera. The seismic energy is recorded as oscillographic traces on sprocket driven film. The film sprocket is rotated by a 100 cps synchronous motor, supplied by a

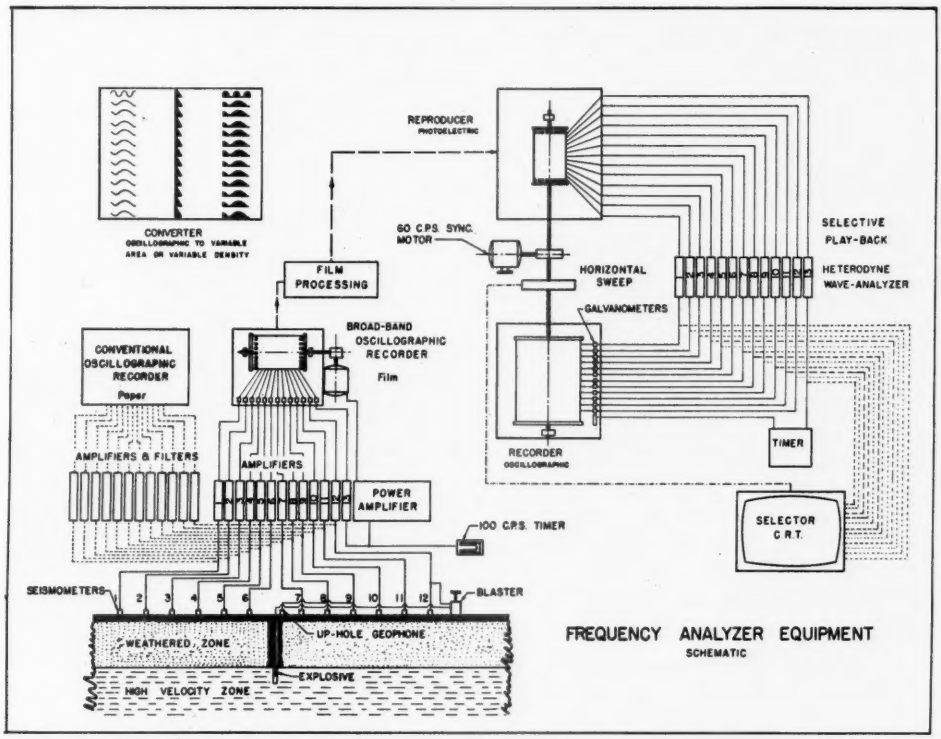

FIG. 1

power amplifier driven by a precision tuning fork. This same fork also drives a galvanometer for placing the timing wave on trace No. 3.

Figure 2 shows the broad-band Recorder and Amplifier unit which is mounted in the field recording truck. The left portion of the cabinet houses the optical and electrical components, while the right portion contains the mechanical film-transport mechanism. Standard 200 feet roll, 35 mm motion picture film is used for the 13 channel recordings, and 70 mm film for the 25 channel recording.

The Recorder employs 600 cps ribbon galvanometers of special design, with a power input of less than one milliwatt for 100 percent excursion of the oscillographic trace. The galvanometers are driven by high fidelity miniature tube amplifiers, which comprise chiefly the gain and control stages with only the

necessary low and high cut-off filtering to establish the limits of the recording. The desired sharp filtering (and mixing if desired) is applied later when the film is played-back through the reproducer. A magnifying telescope is provided for adjusting the amplitudes of the traces. A footage counter records the film exposed.

Upon completion of the recordings, the film is delivered to the computing

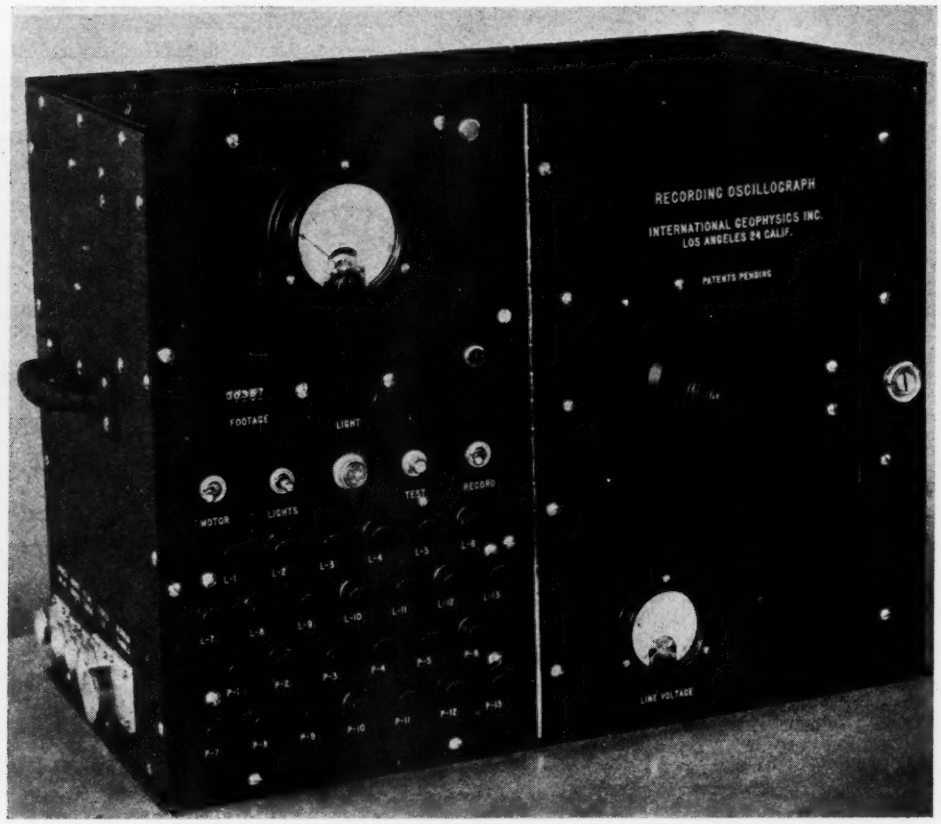

FIG. 2

office where it is photographically processed in a conventional, portable-type developing tank. This operation requires about 45 minutes. No attempt is made to develop the 35 mm film in the field recording truck.

After the roll of film has been processed it is cut into sections, each of which covers the broad-band recording from one shot. Each section of film is then spliced into a closed loop for use in the Reproducer. During the play-back, the film loop is repetitively passed through the Reproducer in such a manner that each trace intercepts a separate portion of the illumination passing from an exciter lamp to a photocell for each trace. The excursions of the oscillographic trace moving past the scanning slot, in combination with a light wedge which varies

the intensity of the illumination with the position of the trace, cause corresponding variations in output of the photocell actuated by that trace. The output of the photocell is then amplified and passed through the desired electrical circuitry. In the particular studies described in this paper we were concerned primarily with selecting certain frequency components of seismic waves. Accordingly, the amplified output from each trace was passed through a specially designed heterodyne-type wave-analyzer and separated electrically by filtering which passed the desired frequency component under study. The filtering employed in this

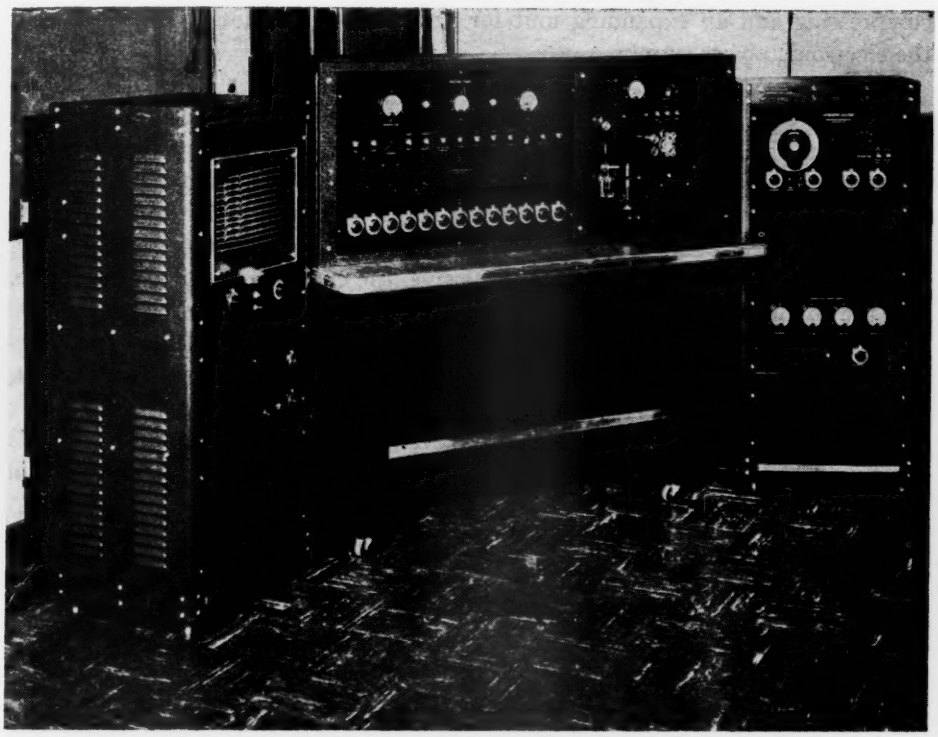

FIG. 3

analysis may be of any desired band-width, and either cut-off edge of the filter may be positioned at any frequency within the frequency spectrum. A multistage, cascade LC Band-pass filter system is employed, having 40 db/octave slopes on both the low and the high frequency sides.

The effects of changes in the filtering or other electrical parameters upon the character and line-up of reflections at the desired depth of investigation may be observed visually upon a 16 inch Cathode ray selector tube. After selecting the desired condition, a conventional paper record may be made for computing and interpretation. Timing lines are placed on this record by means of an electronic

glow-tube timer, actuated by the 100 cps timing wave which was recorded on the film when the original broad-band record was made in the field recorder.

Figure 3 is a view of the wave analyzing equipment; this instrumentation remains at a central computing office and incorporates the necessary mixing, filtering, and expanding circuits. The main control panel is in the center cabinet and comprises separate gain controls for setting the level of each channel and the mixing and control circuits. To the right of the control panel may be seen the film transport mechanism. The left cabinet contains the cathode-ray tube and electronic timer. The right cabinet contains the heterodyne wave-analyzer, a compressing and an expanding unit for accentuating certain components, and the electronic power supply.

SEISMIC PULSE GENERATION

In using the seismograph as a prospecting tool, it is customary to generate a seismic impulse by detonating an explosive of the desired characteristics. The explosion constitutes a very intense point-source of energy. The explosion itself may occur within a time period measurable in micro- or milli-seconds, depending upon the nature and amount of the explosive, the environment of the shot-hole, and the conditions of loading.

Sharpe, Morris* and others have shown that the the initial wavefront is very steep but is modified immediately by the materials surrounding the shot-point, and thereafter is rapidly and progressively reduced in steepness within a few tens of feet. The rate of change of the wave-front is governed primarily by its geometrical expansion and by the transmission and reflection characteristics of the material through which it passes.

FREQUENCY AND ATTENUATION

The spectral distribution of energy in the original impulse is subject to wide variation, depending on the particular conditions and materials adjacent to and in the near vicinity of the explosive. In general, however, its initial energy contains a relatively wide band of frequencies, from a few cycles to many thousand cycles per second. Previous papers by Born and Clewell and Simon† have shown that as this broad-band impulse travels through the earth, its higher frequencies are lost much more rapidly than its lower frequencies, due largely to absorption and scattering. Also, for the lower frequency part of the spectrum there is a

* Joseph A. Sharp, "The Production of Elastic Waves by Explosion Pressures," *Geophysics*' VII, 2 and 3 (1942).

Geo. Morris, "Some Considerations of the Mechanism of the Generation of Seismic Waves by Explosives," *Geophysics*, XV, 1 (1950).

† W. T. Born, "The Attenuation Constant of Earth Materials," *Geophysics*, VI, 2 (1941)

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D. H. Clewell and R. F. Simon, *Exploration Geophysics*, Trija Publishing Company, Los Angeles 24, Calif., 2nd Edition (1950), pp. 661–663.

frequency discrimination for reflected waves which, according to a prevalent theory, is believed to be due to the inter-action between the reflections from the top and bottom interfaces of a given reflecting bed. If the bed is an odd number of quarter-wave-lengths in thickness, the energy from the lower interface will be of opposite phase and interfere with the energy from the upper interface, and the resultant wave motions of that particular frequency will tend to cancel each other. If the thickness of the bed is substantially an even number of quarter-wave-lengths, then the reflections from the upper and the lower interfaces will be of like phase and their effects will be additive, with a resultant increase in effective wave amplitude.

At the longer wave-lengths, where the thickness of the beds is much less than one-quarter wave-length, the effect is believed to be such that the reflection co-efficient falls off more or less directly with frequency, and a stratified earth composed of a sequence of relatively thin beds tends to be homogeneous to the longer wave-lengths; the low frequency energy is not reflected appreciably and is returned to the surface only by refraction.

Therefore, due to the phenomena of absorption and scattering, and of the change in reflection co-efficient, the earth acts somewhat like a wide pass "filter." In each area therefore certain of the reflected frequencies will be accentuated and others suppressed. These reflected bands of signal energy will be superimposed on the interfering energy components which arrive via refraction, air waves, and the surface waves, all of which are received by the seismometer and then recorded.

REFLECTIONS AND INTERFERENCE

The total energy received by the seismometer is a most complex vibration, with preponderantly random relationships in amplitude, phase, and time of duration of its various components.

Figure 4 is a frequency spectrum of the reflections from an area in Louisiana. This illustration is somewhat typical in that it shows the relatively greater amplitudes of the lower frequencies, and the gradual decrease in energy for the higher frequencies. The distribution of recorded energy is further modified by the characteristics of the seismometer and its planting or contact with the ground. For the particular test illustrated, a 0.7 damped, flat response seismometer, with a natural period at about 6.5 cycles, was employed. When the more conventional higher frequency peaked seismometers are used, there is of course, an accentuation of the medium frequencies, depending upon the degree of damping.

Contrary to popular belief, in most areas there exist too many reflecting bands, rather than too few. A poor shooting area generally is caused by too much reflected, refracted, and random energy, with many of the interfering bands at about the same energy level.

A good shooting area generally is one where the reflected bands are sufficiently separated in their times of arrival, and with an energy level appreciably higher

than the background noise or interference. Under these conditions little filtering is necessary to obtain records that will have the desired visual appeal and will yield reliable information. If, however, the higher energy components are not of prime interest, they may mask the lower energy components which are of interest.

Interfering energy may be classified under two general types. One type of interference is created by seismic energy which occupies a position in the frequency spectrum outside of the desired reflecting bands. The other type of in-

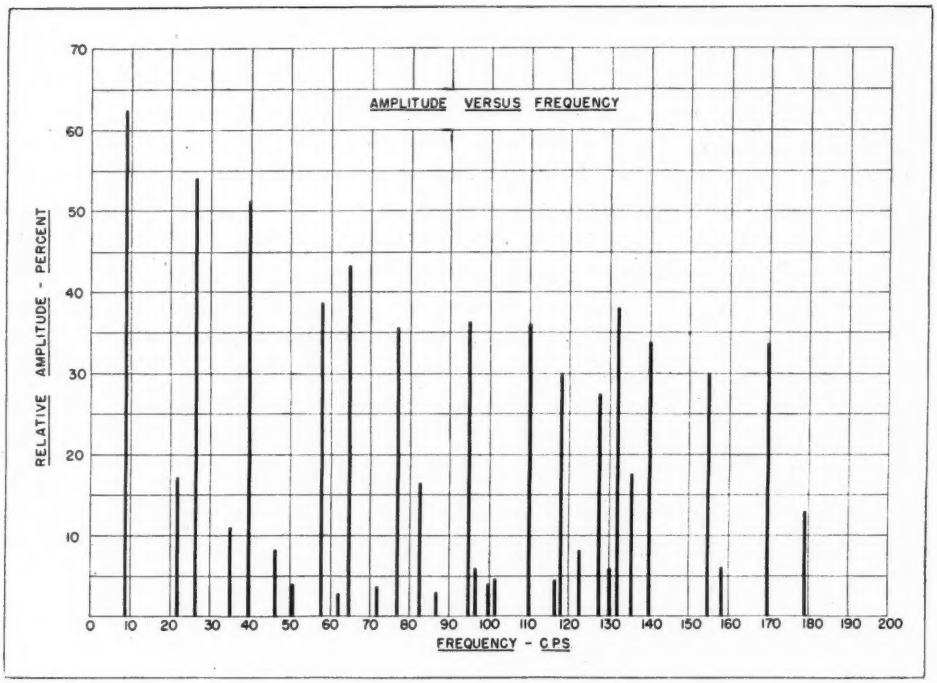

FIG. 4

terference may be created between two or more reflections or between a reflection and interference within the desired reflecting bands.

An illustration of the first classification is when the interference comes from the low frequency part of the spectrum, i.e., at a frequency lower than the reflections of interest. Under these conditions, the signal/interference ratio may be improved merely by employing a high-pass filter which will be so positioned in the frequency spectrum that is lower cut-off will reject the undesirable low-frequency interference. The filter band-width is not critical, but usually it is advantageous to employ as wide a band-width as possible to give sharper onsets and to preserve record character. In like manner, when the interference comes from the high frequency portion of the spectrum, such as wind or shot noise,

and high frequency near-surface beds, records may be obtained usually by employing filtering with the proper high-frequency cut-off.

The second classification of interference presents a more difficult problem. To separate and utilize these components, the filtering often is critical. This condition appears to be accentuated in these areas where the geologic column has bedded strata whose thicknesses and reflection co-efficients are similar and produce reflected energy components of about the same amplitude and which lie within a narrow range of the frequency spectrum. To obtain a more optimum signal/interference ratio from reflectors of this nature, it is necessary to utilize sharp filtering to separate the interfering frequencies. At this point it may be well to differentiate between the effects of sharp filtering and narrow filtering.

Narrow filtering generally is obtained by use of a peaked or resonant type filter passing a narrow band-width at the center or peak frequency of its amplitude-frequency curve. Usually such a filter is of low damping and usually possesses considerable "ring" which tends to destroy the character of the reflected energy. In particular, this type of filter is most undesirable in areas where the reflections follow each other at time intervals less than the time duration of the "ring." When this occurs, the separate reflections tend to merge into one continuous "ring" or train of waves which lack the necessary character to allow correlation or identification of the individual reflections.

Sharp filtering however may be obtained by use of a multisection, nonresonant type filter whose frequency-amplitude curve has steep sides and a fairly flat-top portion of relatively wide band-width. This type of filter can be used to discriminate between two components of different frequencies by adjusting the filter so that the *desired* component lies within the bandwidth of the filter, while the *undesired* component lies outside of the filter curve. When this is possible, the rejection is obtained by means of the steep side of the filter curve and not because of a peak or resonate condition. By making the band-width sufficiently wide, the character of the desired reflection may be preserved and good identification and correlation obtained.

QUALITY OF REFLECTIONS

The quality of the reflection is judged chiefly by its line-up, repetitive pattern, amplitude, envelope, and alignment curvature.* The accuracy of dip computation is dependent upon alignment, and major emphasis usually falls on the outer traces of the record. Minor deviations from the alignment curvature may often be neglected, but there should be no serious and unaccounted for interruptions in the slope of the alignment. Apart from the effect of structural discontinuities, there are two general effects which can cause apparent misalignment. These effects may be classified under the heading of (1) topography and weathering, and (2) phase-shift and modulation. The effects of topography and weathering are well known and need not be discussed here. The effects of phase-shift

* Gaby, Phil P., "Grading System for Seismic Reflections." *Geophysics*, XII, 4 (1947).

and modulation, due to interference between the desired reflection and the undesirable energy, can not be computed, and can be minimized to about the same order of magnitude as the interference itself is minimized.

LOW FREQUENCY INTERFERENCE

Low frequency interference is generally caused by direct or surface waves, shallow refracted waves, and other more or less random energy, including air waves. These interfering waves actuate the seismometers and often produce on the record larger amplitudes than the desired reflected waves. If the amplitude of the interfering waves is sufficient to overload the seismometers and/or amplifiers at the instant the desired reflections arrive, the quality and character of the resulting record will be impaired. Even if the amplitude is below the overload point, the presence of these random waves may make it difficult visually to distinguish the reflected waves. As is well known it is usually difficult to pick a reflected wave in the initial part of the recording period, due to the high energy of the direct waves in the immediate vicinity of the shot point. In like manner, any energy having a level greater than the desired reflections will operate the AGC system of the amplifiers and effectively modulate the amplitude of the reflections. This condition often occurs when high amplitude surface waves actuate the AGC and pinch down the normal amplitude of the reflections and thereby impair the line-up across the record.

Figure 5 illustrates interference from both the low and high frequency ends of the spectrum. This is a recording obtained near Stillwater, Oklahoma. Record I is the original broad-band recording, without filtering. The first arrivals are shown at *A* traveling at a velocity of 7,200 feet per second. Two low frequency disturbances may be seen cutting across the record, at *B* and *C*. Superimposed on the traces may be seen indications of some higher frequency energy having a frequency of about 100 cps. At *D* and *E* there is an indication of a line-up of reflected energy.

In Record II, the low frequency components are shown and comprise the 21 cps surface longitudinal waves *B* traveling at a velocity of about 2,100 feet per second, and the 19 cps air waves *C* traveling with a velocity of about 1,090 feet per second.

Record III shows the higher frequency components which constitute the reflections at the desired depth range coming in at a frequency of 68 cps. Record IV shows the 93 cps component.

It may be of interest to note that the first arrivals are not discernible on Record II, the low frequency record; while they are easily seen on the broad-band Record, No. I. These first arrivals are the direct and shallow refracted waves, and in this case due to the short distance of travel, include a good percentage of high frequency components. Record I illustrates the well known fact that to obtain sharp first arrivals the high frequency components should be passed by the filtering system during the initial part of the recording.

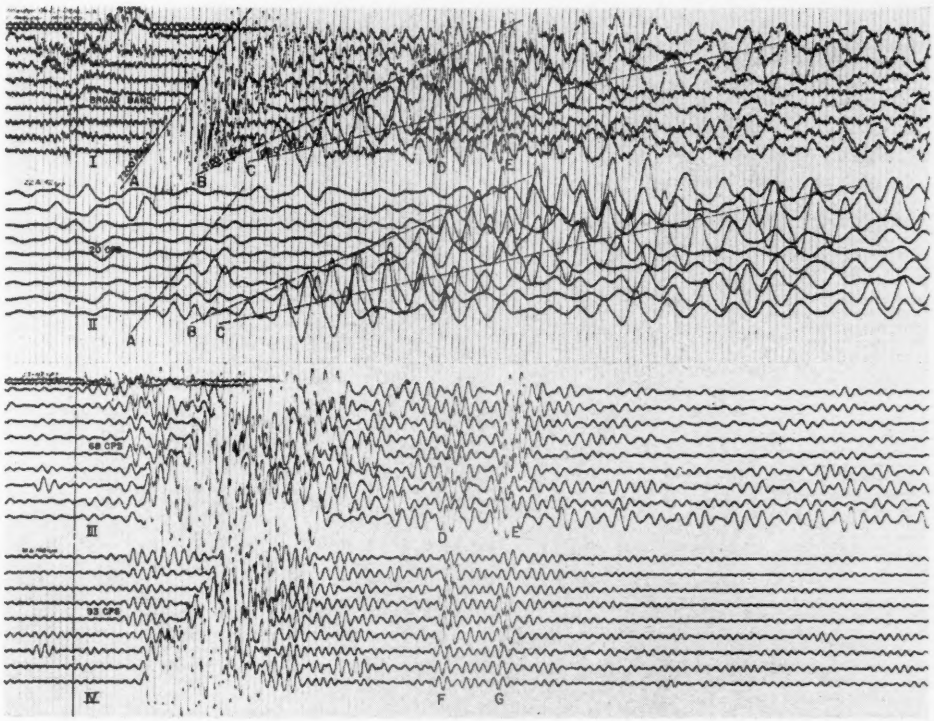

FIG. 5

INTERFERENCE BETWEEN REFLECTIONS

As was previously outlined, interference also may occur between reflections. This condition is illustrated in Figure 6; a record taken in the Haskell Reef Area of Texas. In this part of the area poor records are obtained when using the conventional recording techniques. The broad-band record is shown at I, and reflected energy may be seen cutting across the record at *K*, *J*, *I*, *B*, *A*, and *D*. The low frequency components are shown in Record II. Cutting across that record may be seen a 17 cps surface wave. The 47 cycle reflections are shown at *J*, *I*, *B*, *F* and *D* in Record III, and a 62 cps reflection at *K* in Record *IV*. Based on travel times, the reflection at *K* is in the reef material of middle Pennsylvanian Age. The reflection at *I* is near the bottom of the Pennsylvanian and the one at *B* is probably from the Ellenberger. Note the reversal in apparent ΔT between the shallow reef reflection at *K* (+9 milliseconds), and the deeper reflections from below the base of the reef (−6 at *B* and −7 at *D*).

CHANGES IN ΔT CAUSED BY INTERFERENCE

Interference between reflections of substantially the same amplitude may introduce errors in the observed values of ΔT. This condition may be illustrated

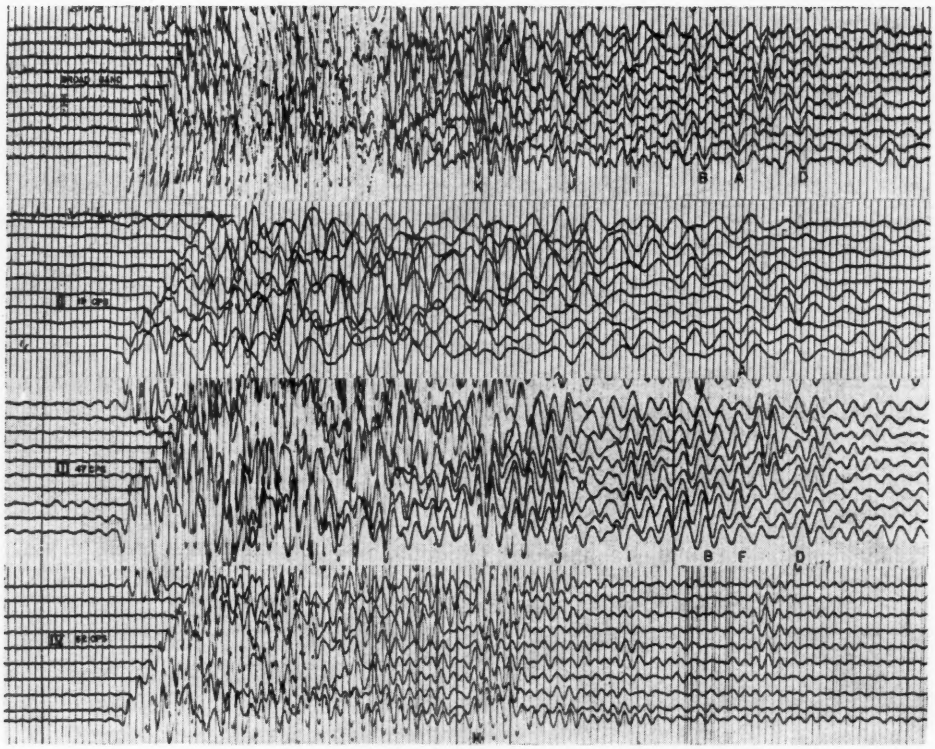

FIG. 6

by the diagrams in Figure 7. Diagram I illustrates a shot point located at SP, the near seismometer at S_1, and the far seismometer at S_{10}. Assume two reflections of different frequencies, say 30 and 40 cps, of about equal amplitude and from the same reflecting horizon. If the onsets of both reflections occur simultaneously at the near seismometer, the relationships will be as illustrated by Diagram II. Let A represent the first trough for the higher frequency wave, and B represent the first trough for the lower frequency wave. Since the two troughs have the same relative phase angle, their effects will be additive, to give a resultant trough at T_1. By like reasoning, the peaks are located at C and D, with the resultant peak at T_2.

At the far seismometer the relationships may be as illustrated by Diagram III. The greater distance traveled by the wave will produce the relative phase displacements as illustrated, making a greater shift in the resultant trough T_3 and the resultant peak T_4. The value of ΔT will, therefore, be greater than its true value when the waves exhibit phase relations as illustrated; and likewise it will be of lower value for reversed conditions. Also, if the pulses overlap for a sufficient time duration, the differences in ΔT values will be greater for the second series of troughs and peaks. Oftentimes this furnishes a check on the presence of

interfering reflections which are additive and slightly out of phase. When this condition exists, the ΔT values across the record, between corresponding troughs and peaks, will vary progressively between the first set of troughs, and the first set of peaks, the second set of troughs, the second set of peaks, etc.

A reflection of this type will have "character" across the record and will break into two separate legs when the interfering components differ sufficiently in phase. The required phase difference between the two reflections will depend

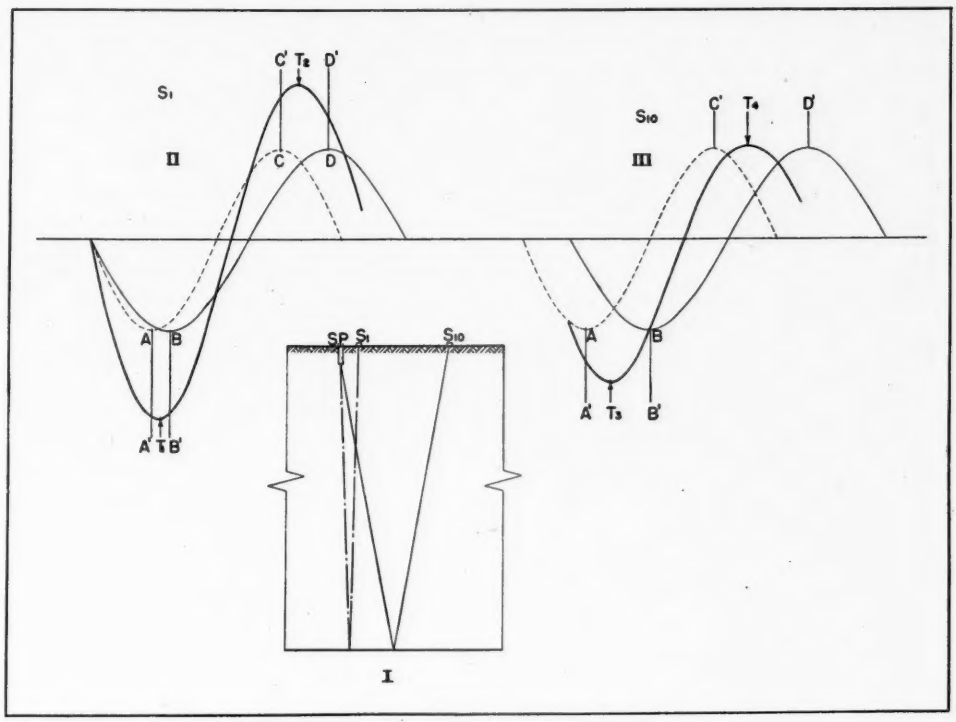

FIG. 7

upon the difference in frequency and upon the filter characteristics; the more "ring" in the filter the greater must be the frequency difference. When good separation is obtained, each of the separate components will have substantially the same ΔT value. Generally, by sharp filtering, either of the component reflections may be recorded if their frequency difference is sufficient to allow the cut-off edge of the filter to be positioned between the two frequencies. This required frequency difference therefore is dependent also upon the steepness of the edges of the filter.

In the previous illustration, two interfering waves of equal magnitude were drawn. Generally, however, one wave will have greater amplitude and as a

result, will predominate. The shift in ΔT value caused by the interference then decreases in reference to the stronger wave.

An interference between waves of about the same amplitude may be seen in Figure 8, showing portion of a record taken in Louisiana. The top record of this figure shows the wave motion at periods *A* and *B* for a 36 cps wave meeting interference from a 25 cps wave. The step-out time between the two outside

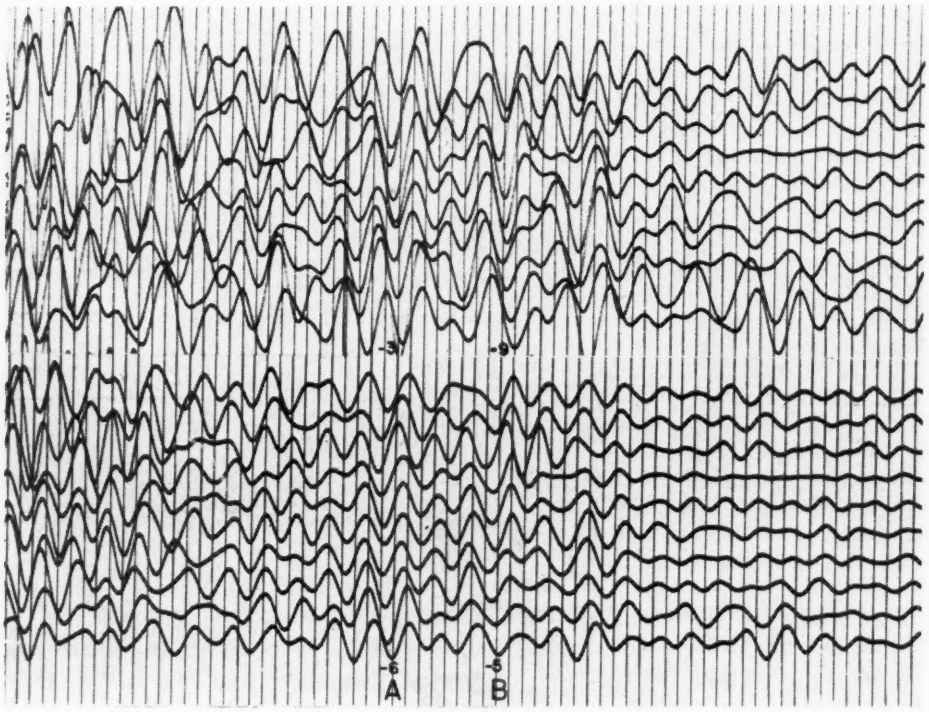

FIG. 8

traces is -3 milliseconds at Point A, and -9 milliseconds at Point B. The lower record of this figure shows the 36 cycle component with substantially all of the interference removed, with step-out times of about -6 milliseconds on each reflection. These values are in agreement with the tie-in times to the adjacent profiles of the traverse, and probably represent the normal values.

Figure 9 is included in this paper to illustrate the effect of filter width on record "character." The top record is the original broad-band recording, taken in the Outlook Area of Canada. The second record was recorded through a 12 cps wide filter; the third record through a 30 cps filter, and the fourth record through a 40 cps filter. All filters were centered at 45 cps. As the filter width is increased, more interfering energy is admitted, with resultant changes in record

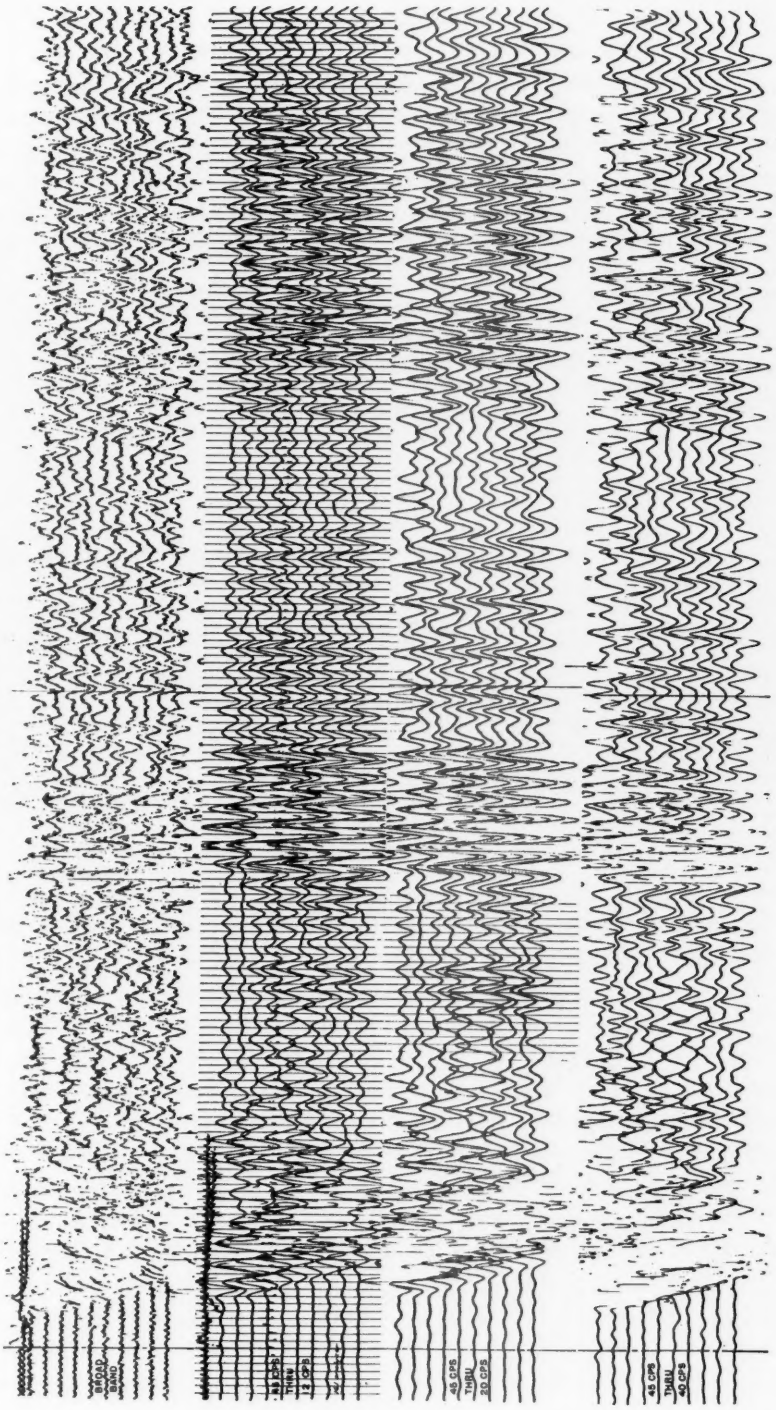

FIG. 9

character. In this particular case the major interference is caused by a 54 cps component on the high side of the desired reflections centered at 47 cps.

It is of interest to note the increasing sharpness of the first arrivals, the increased record "character," and the better separation of the reflections as the band-width is increased. The "ring" from the 12 cycle filter destroys the character of the reflections and masks the reflections which follow the big reflection. In this area, discrimination is obtained by using the edges of a broad-band filter in preference to the peak of a narrow filter.

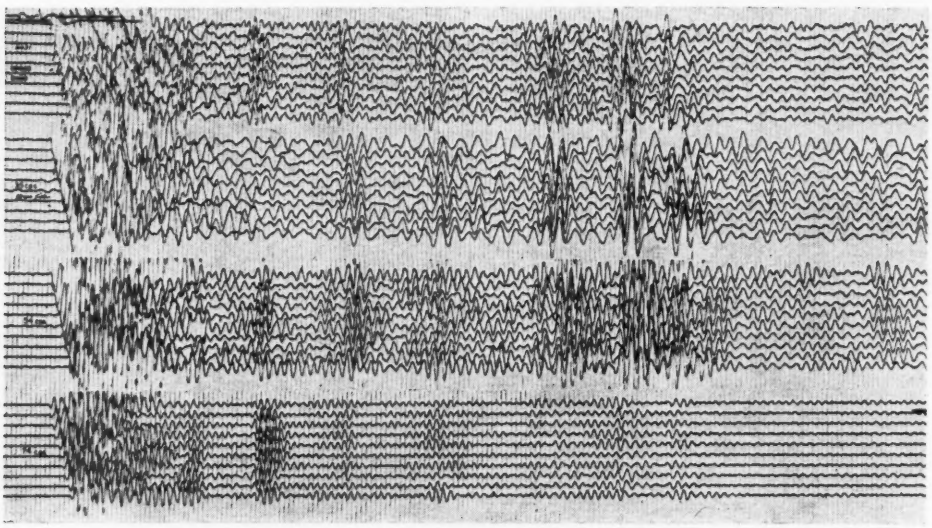

FIG. 10

Figure 10 is a record from the Shaunavon Area, Canada. A 20 cps wide filter was employed, with the filter centered at 35, 54, and 74 cps. It is of interest to note the greater depth from which the 35 cps reflections are received, after the big reflection. The 54 cps reflections gave better detail in the middle part of the record but are absent after the big reflection. The 74 cps reflections supply detail in the shallow part of the record. These filtering tests were made at the same amplifier gain and give a fairly good comparison of the relative amplitudes of the different frequency reflections in this particular area.

This slide also illustrates one practical advantage of the broad-band recording technique when applied to this particular area. The three lower records have filtering frequencies which differ sufficiently so that multiple recording or two or three shots at different filtering frequencies would have been necessary to bring in the reflections, due to the narrow filtering required. When the filtering was broadened sufficiently to cover two or three of the reflection frequencies, the quality of the record suffered due to interference. In this case, a single shot with broad-band recording, which later is played-back through the desired

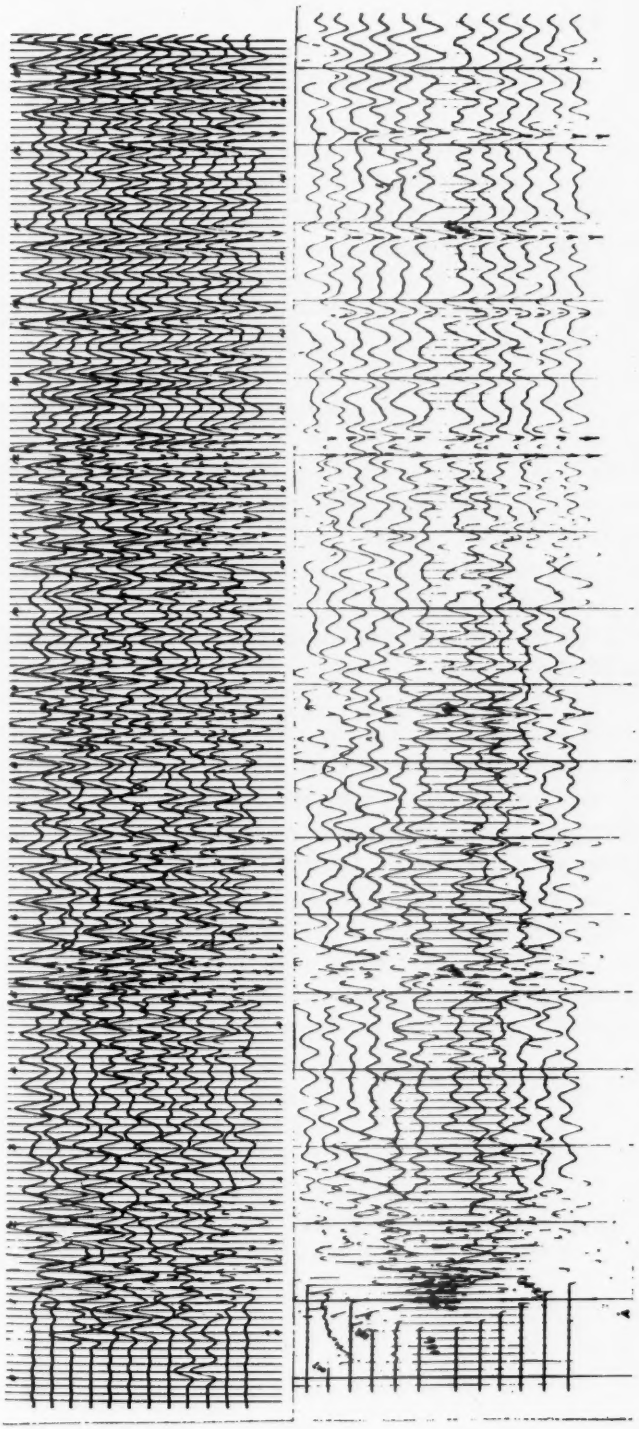

FIG. 11

narrow filtering, yields results comparable to two or three shots, each taken through narrow filtering. Under this condition the broad-band recording technique often minimizes the number of shots in each shot-hole which results in a saving in the amount of explosive used and in crew-time.

Probably the chief application of the play-back technique will be its use in the "marginal" or more difficult areas where records of poor quality are generally obtained. For much of our work in this type of application, only sufficient filtering was employed during the original recording to remove the major interference frequencies that may lie above or below the band-width that will adequately cover the frequencies of the desired deep and shallow reflections in the area. Generally this band-width will be about 40 cycles wide and so positioned in the frequency spectrum as to encompass both the high and low frequencies. No attempt is made in the field to accurately select the optimum filtering or frequency setting.

During the play-back the Reproducer operator may remove his normal inhibitions and conveniently experiment with any desired combination of filtering, mixing, amplitude and modification (expansion or compression) which his previous experience or intuition may indicate desirable. Many combinations may be tried within a few minutes time and their resultant effects observed on the oscilloscope tube. When optimum results are obtained, the paper record may be made for use in the computing.

Figure 11 illustrates this general result. The top record is the play-back record used for computing, while the lower record is the original recording received from the conventional seismic equipment in the field truck. Although both records contain substantially the same information, the "cleaned-up" record speeds up the interpretation by improving the definiteness of correlation and the consistency of the computed results. Much less "adjusting" is necessary in the final interpretation. In nearly every marginal area worked to date it has been our experience that the general quality of the records can be raised one or two grades by use of the play-back technique. The time saved in the computing and interpretation more than offsets the time required for the play-back procedure.

VARIATION OF ELASTIC WAVE VELOCITY WITH SATURATION IN SANDSTONE*

D. S. HUGHES† AND J. L. KELLY†

ABSTRACT

The velocity of dilatational waves in four sandstones has been measured as a function of pressure in the range 50 to 1000 bars at room temperature and at 100°C. At least two cores from each sample were run, one dry and one saturated with water. In addition two cores from one sample were run at several partial saturations. The porosities of the samples varied from about 8 to 20 percent. The effect of water content is dependent on pressure. At low pressures (50 bars) the velocity rises sharply at small saturations (0–10 percent), remains constant with saturation 10 to 90 percent and then decreases as the saturation approaches 100 percent. At 50 bars the velocity at 100 percent saturation is generally higher than that at 00 percent saturation. Even for the one exception an extrapolation would indicate this to be true at atmospheric pressure. As the pressure is increased the rise at low saturations decreases; at 500 bars it disappears. The velocity is almost constant with saturation until about 90 percent saturation is reached. It then decreases rapidly as 100 percent saturation is approached.

A qualitative explanation of these results is given.

INTRODUCTION

The effect of water content on elastic velocity has been studied by several investigators. There is some discrepancy in results; thus Oliphant (1950) and Born and Owen (1935) found that slight additions of water caused a sharp drop in velocity with a following slow decrease as the saturation approached 100 percent. Both investigators worked at atmospheric pressure and actually measured the bar resonant frequency. From this Young's modulus of the sample was computed, and from measured or estimated values of Poisson's ratio the dilatational velocity was computed. Hughes and Jones (1950) measured the dilatational velocity directly by measuring the time of transmission of pulses through the sample. In this work the sample was held under hydrostatic pressure, 50–6,000 bars, and it was found that fluid tended to increase the velocity at low hydrostatic pressures and decrease it at high pressures. The fluid admitted to the rock was No. 10 motor oil. In this work the only samples measured were of very low porosity, less than 1 percent. Using the same apparatus and methods, Hughes and Cross (1951) measured the velocity in Solenhofen limestone (porosity 4 percent) and Caplen Dome sandstone (porosity 5 percent) for dry and saturated samples. For both materials the variation of velocity with pressure was small and linear for the saturated samples. The dry Solenhofen samples also showed a slow linear increase with pressure. At low pressures the dry velocity was slightly higher, about 5 percent, than the saturated. As the pressure increased the curves

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approached and crossed so that at 5,000 bars the saturated velocity was some 10 percent higher. The Caplen Dome sandstone showed a different behavior. In the dry sample the velocity at low pressures was much smaller than in the saturated, 3,672 meters/sec against 4,453 meters/sec. As the pressure increased the dry velocity rose very rapidly so that at 500 bars it was 4,577 meters/sec as compared to 4,505 meters/sec in the saturated core. It continued to rise rapidly with pressure and at 5,000 bars was 5,363 meters/sec as compared to 4,887 meters/sec in the saturated core. These results are similar to those found by Hughes and Jones (1950) but the order of magnitude of the variations are much greater.

The results described above were obtained more or less incidentally in the course of other work. In an attempt to resolve this question it was decided to undertake a more elaborate investigation.

EXPERIMENTAL PROCEDURE

The pressure apparatus and method of measuring the velocity were similar to that described by Hughes and Cross (1951). The pressure was restricted to the range 50–1,000 bars or approximately 14,500 psi. Measurements were made at room temperature and 100°C. except in one case where an upper temperature of 150°C. was used. The pressure and temperature ranges were restricted in an attempt to avoid permanent changes in the cores. Only the dilatational velocity was measured. The secondary arrivals are always poor in very porous rocks and thus the rotational velocity could not be measured.

In brief the velocity is measured as follows. A core 1.0 inch in diameter by 2–3 inches long is cut from the sample. This core is enclosed in a composite jacket of thin copper and neoprene tubing, Figure 1, to exclude the pressure fluid. Quartz crystals are mounted on each end. A sharp pulse, rise time 0.1 μ sec, is impressed on one crystal and the time of arrival at the second crystal measured. These times are of the order of 15–25 μ sec. The accuracy with which the arrival time can be read depends upon the quality of the received wave. For all results reported here this accuracy is at least 0.20 μ sec at low hydrostatic pressures and increases rapidly as the pressure is raised. The core and crystals are placed in the pressure chamber and the transmission time measured as a function of pressure. Kerosene was used as the pressure fluid. A furnace can be placed around the chamber and any temperature from room temperature to 300°C. obtained.

The samples used in this work are described below. Three sandstones and one sandy shale were run. As shown below the porosities range from 8 to 20 percent. The cores were drilled from the samples with a diamond drill and the ends sawed off to the proper length. The cores which were water soaked from the drilling and sawing were dried by heating in an oven at 110°C. for 10–12 hours and cooled in a desiccator. The cores that were to be run dry were then jacketed and measured. Cores that were to be saturated were placed in a glass

tube attached to a vacuum pump. The tube containing the core was immersed in boiling water and the pumps were run until the pressure would remain steady at 0.002 millimeters of mercury. The tube containing the core was then sealed off, immersed in distilled water which had been de-aerated by boiling in vacuum, and the tip of the tube broken to admit water to the core. This water-filled tube was then placed in the pressure chamber and the pressure raised to 1,000 bars for several minutes to insure complete water saturation. The tube was then

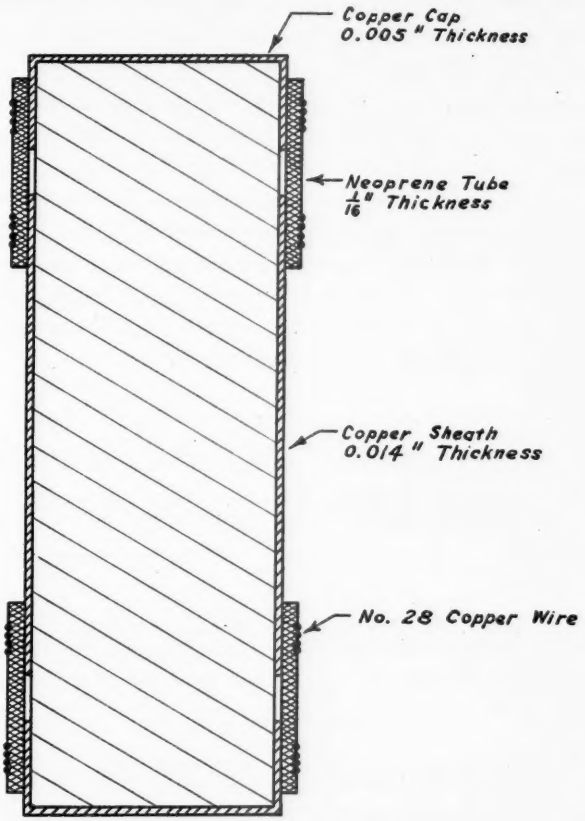

FIG. 1. Core and jacket.

placed under de-aerated distilled water. The glass was broken and the jacket put on the core under water. The assembly was then dried and weighed.

The jacketing material was weighed previously; then from the weight of the dry core and the final weight the quantity of water placed in the sample could be determined. The porosities given below were determined by this method. The partial saturations were achieved by a somewhat different method. The dry core was placed in distilled water, heated and evacuated with an aspirator for several hours. Air was then admitted, and, after a few hours wait to give time

for water penetration, the jacket was placed on the core. Compared with the more elaborate method above this procedure never resulted in more than 90 percent saturation.

The velocity-pressure curve was then run and the core weighed again to determine any gain or loss of weight. The neoprene tubing was removed, the core placed in a desiccator for a short time, then weighed to determine loss of water. When sufficient water was lost the neoprene was replaced and the velocity pressure curve run. This was repeated to give several different saturations.

This procedure is time consuming and only one core was run completely and a second core partially. Weights of all cores were taken before and after every pressure run to make certain that the jackets did not leak. It was found that some cores would increase somewhat in weight, particularly after the high temperature run. These cores also showed large gains in velocity particularly at the lower pressures. Figure 6 is typical of this phenomenon. The weighings before and after runs showed, however, that the core was taking up fluid, probably by diffusion through the neoprene. A partial leak of this sort has never been noted before. In general if the jackets leak at all the core is completely saturated. In cases where there was no gain in weight, i.e., less than six milligrams, the velocity curves could be repeated exactly on successive runs.

RESULTS

The samples studied are described in the following tabulation.

Sample 46: #1 Gov't Downing, Longs Creek, Wyoming. Depth 5,955–5,956 ft. Medium grained, light grey to white Tensleep sandstone (Pennsylvanian).

Core No.	*Density*	*Porosity*
187	2.35 gm/cc	—
188	2.31 gm/cc	13.7%

Sample 48: Frieburg-Altona, #1 (Shell), Natrona Co., Wyoming. Depth, 4,860–4,861 ft. Black silty shale intercalated with sand and shale. Muddy sandstone, Thermopolis shale (Basal Upper Cretaceous).

Core No.	*Density*	*Porosity*
182	2.47 gm/cc	7.9%
183	2.47 gm/cc	—

Sample 52: Paloma Field, Kern Co., California, Depth 10,000 ft. (approx.) Steven Sand (Miocene).

Core No.	*Density*	*Porosity*
193	2.08 gm/cc	—
194	2.08 gm/cc	21.9%

Sample 53: Hare Field, Lea County, New Mexico. Depth 7,795 ft. McKee Sand, Simpson Fm. (Ordovician),

Core No.	*Density*	*Porosity*
189	2.51 gm/cc	8.5%
190	2.51 gm/cc	—

Figures 2, 3, 4, and 5 show plots of the data on the four samples studied. The numerical results are given in Tables I to V. All four samples show very little temperature effect when dry. Sample No. 46, Core 187 was run at 150°C. and actually shows an increase in velocity. This core however gained 0.84 percent

by weight of fluid during the runs and this increase in velocity is almost certainly due to this. The saturated cores show fairly large decreases in velocity with temperature. At the lower pressure limit of 50 bars the dry and saturated velocities are very nearly equal except for Sample No. 48 which appears to be a sandy shale.

With increasing pressure the velocity in dry cores increases much more rapidly

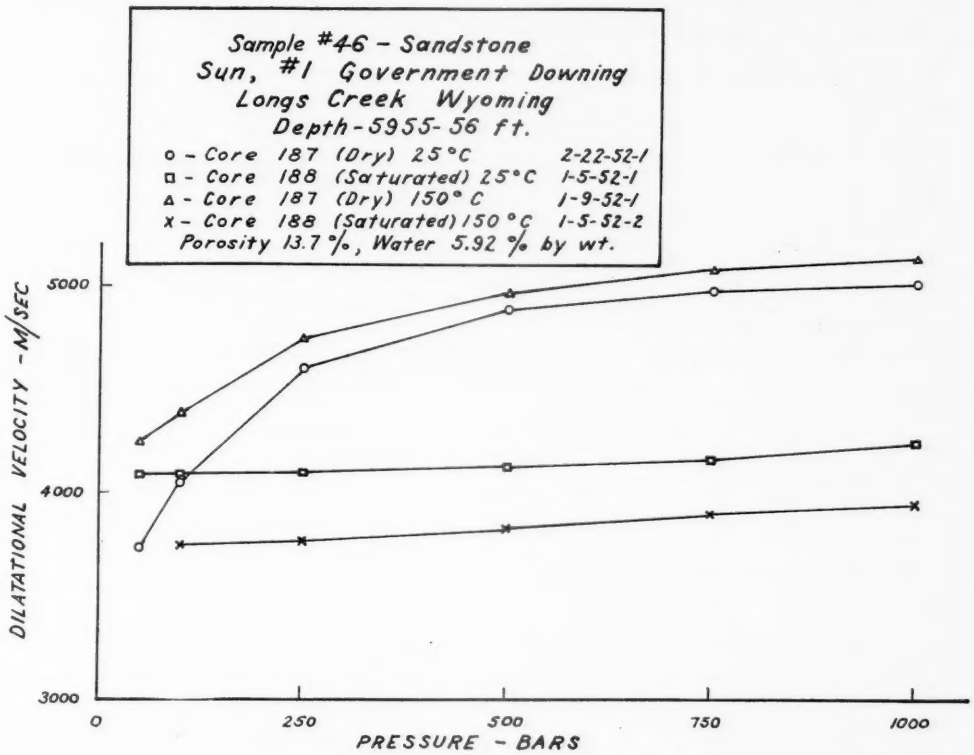

FIG. 2. Dilatational velocity *vs* pressure, Sample 46.

than in the saturated cores. Except for Sample No. 48, the dry velocity at 1,000 bars is 10 to 20 percent greater than the saturated.

In an attempt to determine more exactly the effect of water, Cores No. 187 and No. 188 were saturated by the second method using the aspirator. Since Core No. 187 was never saturated by the exact method, its porosity is not precisely known. Core No. 188 was 92 percent saturated by this method. Figure 7 shows the data at room temperature and 100 percent saturation from Figure 2. A curve was taken at 92 percent saturation. The core was then dried in succession to 88, 37, 15, and 0 percent saturation with velocity pressure curves at each saturation. No difficulty with leaks was encountered during these runs. As presented in Figure 7, these curves are somewhat involved. Figure 8 shows the same

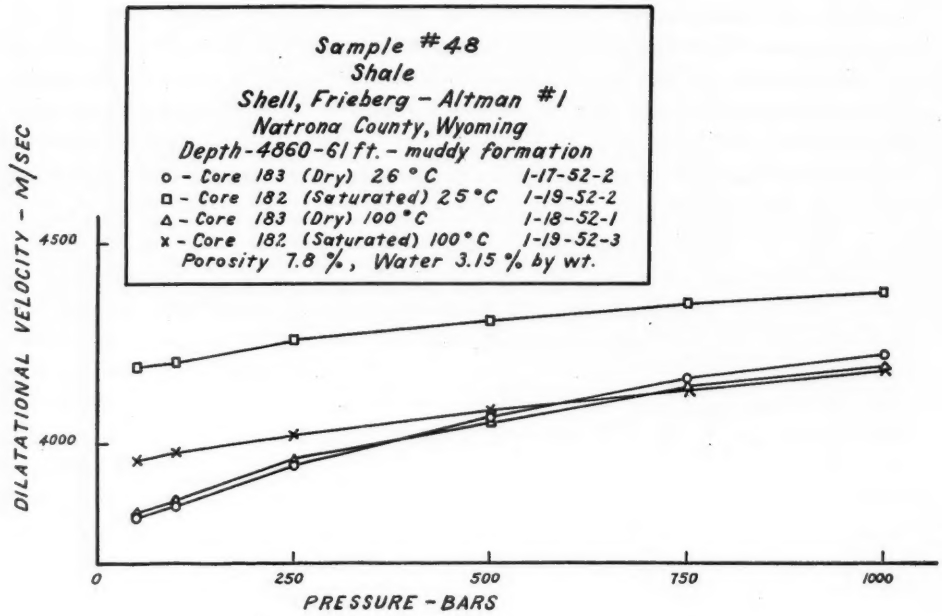

FIG. 3. Dilatational velocity *vs* pressure, Sample 48.

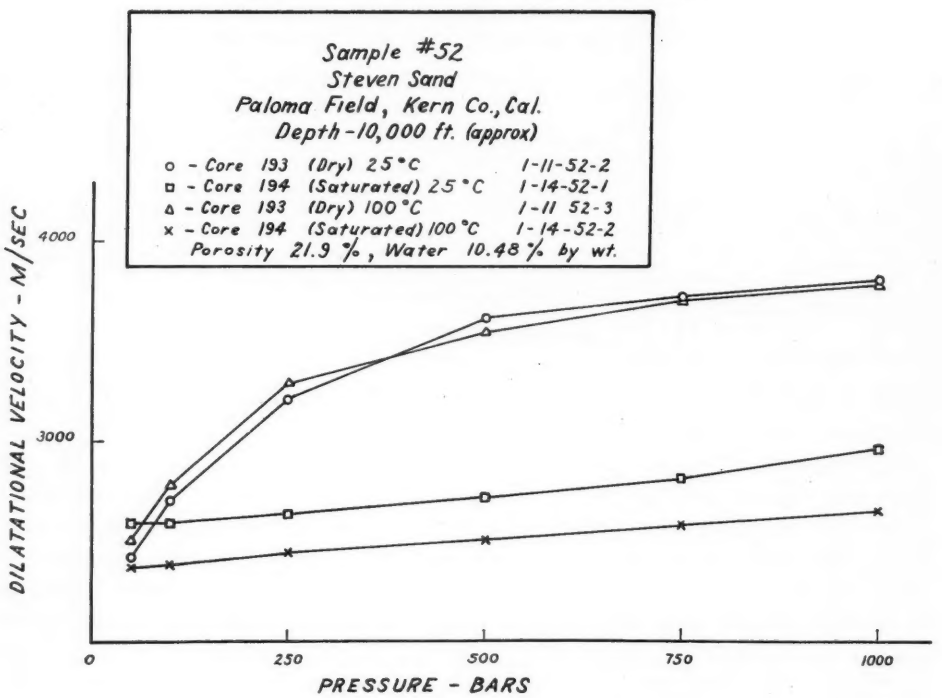

FIG. 4. Dilatational velocity *vs* pressure, Sample 52.

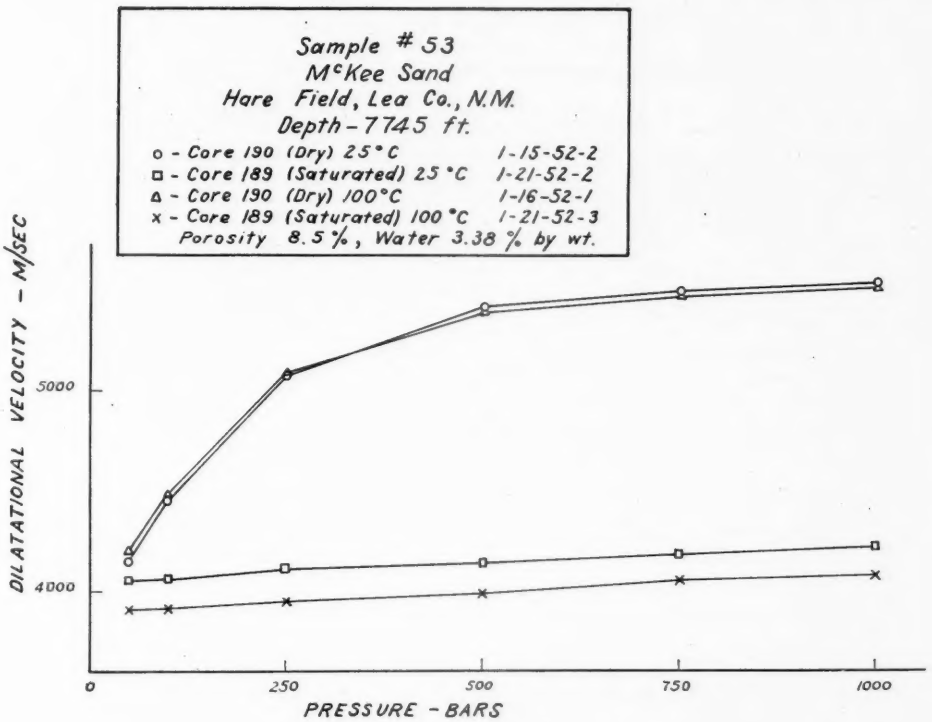

FIG. 5. Dilatational velocity *vs* pressure, Sample 53.

data plotted as a function of saturation for various pressures and Table V lists the data. Figure 9 shows results of plotting weight gains of all the cores that "leaked" against velocity at 50 bars pressure. The 50 bar curve for No. 188 is also shown on this figure. At 50 bars it is evident that an initial small quantity of fluid, one percent by weight, increases the velocity by a considerable factor. For Sample No. 46 this corresponds to about 15 percent saturation. At higher pressures the initial water has no appreciable effect. For saturations of 15 percent

TABLE I

SAMPLE 46

Dilatational Velocity of Dry and Saturated Cores at 25°C. and 150°C.

(meters/sec)

Pressure (bars)	Core 187 Dry 25°C.	Core 188 Sat. 25°C.	Core 187 Dry 150°C.	Core 188 Sat. 150°C.
50	3,825	4,086	4,254	—
100	4,120	4,096	4,390	3,746
250	4,700	4,102	4,751	3,777
500	5,051	4,131	4,968	3,837
750	5,148	4,172	5,089	3,908
1,000	5,187	4,247	5,140	3,951

TABLE II

SAMPLE 48

Dilatational Velocity of Dry and Saturated cores at 25°C. and 100°C.

(meters/sec)

Pressure (bars)	Core 183 Dry 25°C.	Core 182 Sat. 25°C.	Core 183 Dry 100°C.	Core 182 Sat. 100°C.
50	3,819	4,194	3,826	3,963
100	3,846	4,209	3,858	3,983
250	3,947	4,263	3,951	4,027
500	4,066	4,311	4,060	4,083
750	4,165	4,355	4,141	4,135
1,000	4,226	4,382	4,195	4,186

TABLE III

SAMPLE 52

Dilatational Velocity of Dry and Saturated Cores at 25°C. and 100°C.

meters/sec)

Pressure bars)	Core 193 Dry 25°C.	Core 194 Sat. 25°C.	Core 193 Dry 100°C.	Core 194 Sat. 100°C.
50	2,423	2,595	2,514	2,381
100	2,713	2,599	2,793	2,389
250	3,215	2,645	3,296	2,445
500	3,620	2,723	3,557	2,515
750	3,731	2,850	3,726	2,586
1,000	3,806	2,971	3,788	2,658

TABLE IV

SAMPLE 53

Dilatational Velocity for Dry and Saturated Cores at 25°C. and 100°C.

(meters/sec)

Pressure (bars)	Core 190 Dry 25°C.	Core 189 Sat. 25°C.	Core 190 Dry 100°C.	Core 189 Sat. 100°C.
50	4,151	4,065	4,203	3,907
100	4,454	4,077	4,478	3,907
250	5,077	4,100	5,090	3,951
500	5,422	4,142	5,399	3,987
750	5,512	4,182	5,485	4,048
1,000	5,560	4,222	5,526	4,080

TABLE V

SAMPLE 46, CORE 188

Dilatational Velocity (meters/sec) vs. *Pressure and Water Content at 25°C.*

Percent Saturation	100	91.6	87.5	37.4	14.6	00.0
Percent water by weight	5.94	5.44	5.20	2.22	0.87	0.00
Pressure bars)						
50	4,086	4,303	4,460	4,506	4,399	3,730
100	4,096	4,343	4,500	4,592	4,576	4,047
250	4,102	4,447	4,622	4,814	4,814	4,608
500	4,131	4,642	,4775	4,954	4,894	4,893
750	4,172	4,789	4,902	5,023	4,992	4,988
1,000	4,247	4,872	5,019	5,070	5,023	5,027

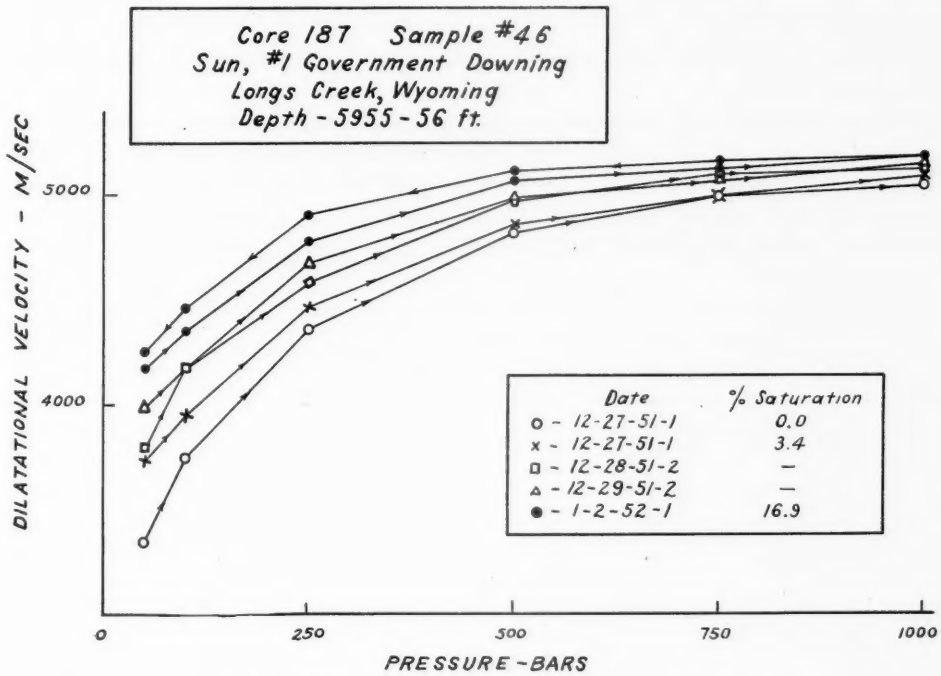

FIG. 6. Dilatational velocity *vs* pressure for successive runs.

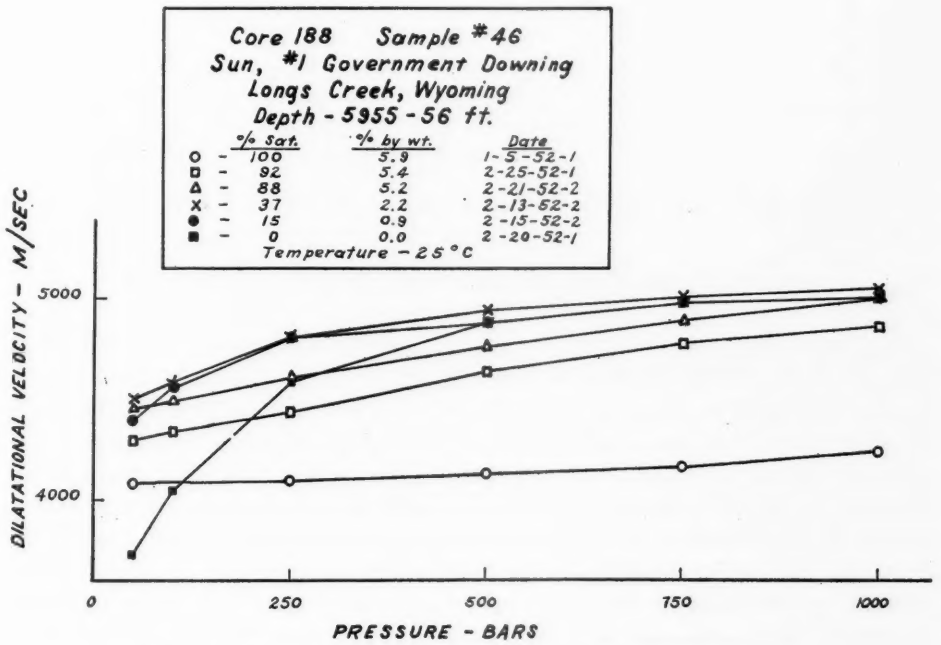

FIG. 7. Dilatational velocity *vs* pressure for various water contents.

to 90 percent, the water has little effect. Above 90 percent, increasing saturation results in considerable decrease in velocity. This decrease is larger for the higher pressures.

Figure 10 has been prepared to show a qualitative interpretation of these data. The rock grains are represented schematically as close-packed spheres. Interstitial water is shown in black, interstitial air in white. These have been drawn for four saturations at three pressures. Considering the dry-low pressure example, the rock grains are in loose contact or more probably have very small

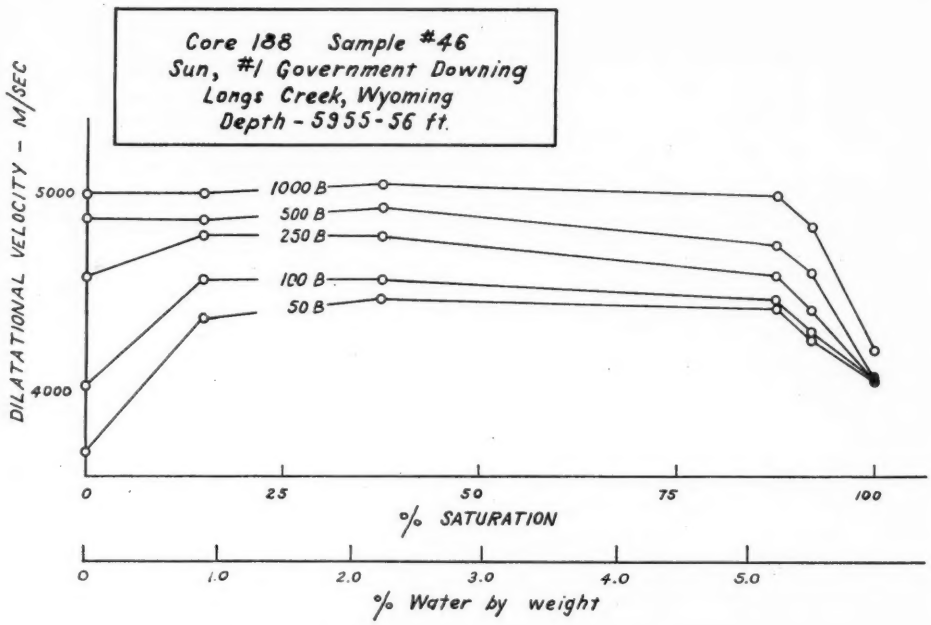

FIG. 8. Dilatational velocity *vs* water content for various pressures.

areas of contact. Raising the pressure increases the area of contact and makes the rock a better acoustic medium. This is checked qualitatively by the fact that a detectible pulse is almost never transmitted through a dry porous rock at atmospheric pressure. A pressure of 20 to 30 bars is usually sufficient to bring in a detectible signal. If a small amount of water is added and if it wets the rock it will be pulled into the smaller cracks or it will serve to effectively increase the area of contact at atmospheric pressure of the grains. Usually a very small quantity of water results in signals. As more water is added the effect would be expected to be small. Considering on the other hand the changes in a rock with high but incomplete saturation, as the pressure is increased the air or vapor bubbles are compressed first and the rock probably compresses similarly to a dry rock. When, however, the bubble disappears the compressibility of the rock

decreases. Following the series showing high pressures at various saturations the contact area of the grains decreases with increasing saturation because the water is less compressible than air.

In comparing the results of various investigators two factors should be kept in mind. Oliphant (1950) and Born (1935) working at atmospheric pressure measured the bar velocity which depends upon Young's modulus. Oliphant also

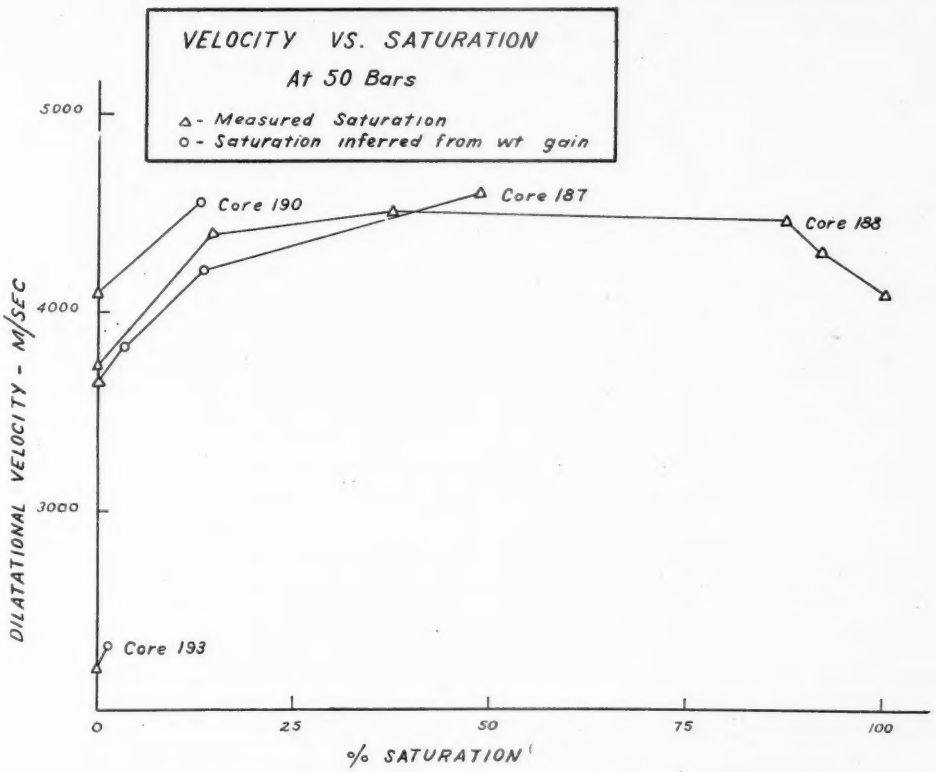

FIG. 9. Dilatational velocity *vs* fluid content for various samples.

measured the rotational velocity and hence computed the dilatational velocity. In our work the dilatational velocity is measured directly with the rock under hydrostatic pressure. It is effectively, however, the velocity of waves in the 1.0 to 5.0 megacycle range whereas the resonance frequencies for the bar velocity are of the order of 5.0 to 50 KC. In our work it is possible that at low pressures our velocities are low because of absorption and dispersion. The highest absorbtion at which we can make measurements is about 15 db/cm. This is roughly 3 db per wave length or an amplitude reduction of about 30 percent per wave length. At high pressure, above 250 bars, the absorption is about 10 db/cm, or roughly 2.0 db per wave length. The amplitude reduction is about 20 percent

per wave length. The few direct comparisons available between our results and results of other methods has so far shown no discrepancy attributable to dispersion.

The velocity of elastic waves through a hexagonal packing of spheres has

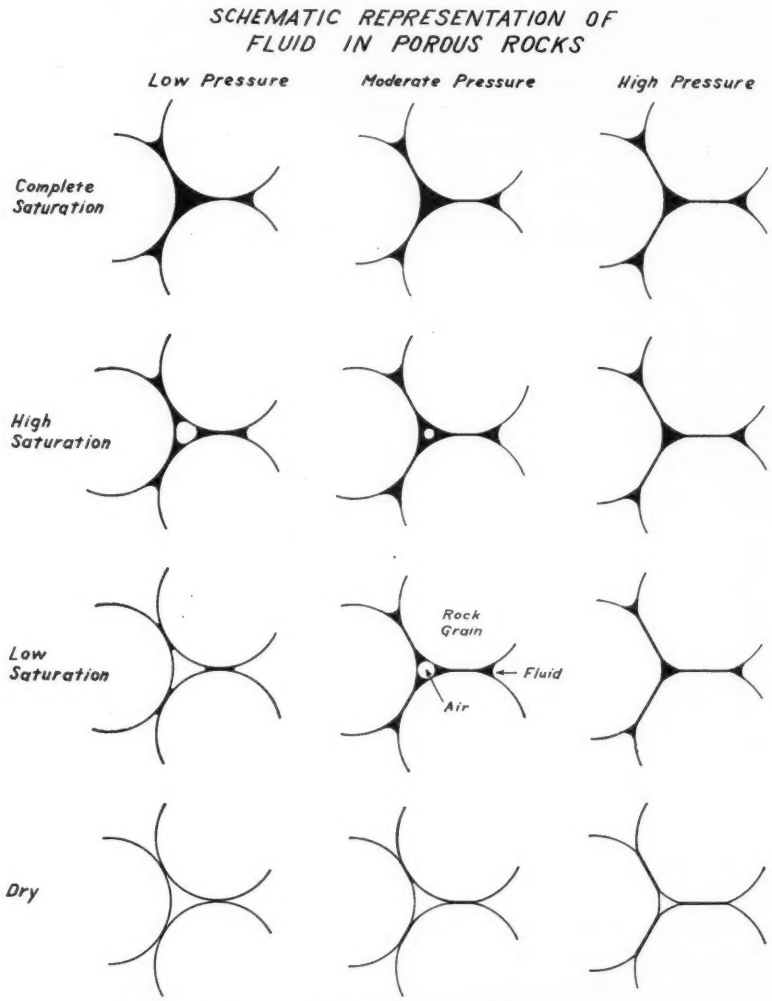

FIG. 10. Schematic representation of fluid in porous rocks.

been considered by Gassman (1951). This model is similar to our Figure 9. This is a reasonable model on which to base a qualitative study of elastic velocities in dry and saturated sandstones. Two rather serious disadvantages of this model should be noted. One is that the infinitesimal theory used by Gassman cannot take into account the decrease of pore space with increasing pressure in the dry

system. The other is the anisotropy introduced by the assumption of hexagonal packing which would not be present with random packing. A third and less serious discrepancy is that the porosity of the system is fixed at the rather large value of 26 percent.

Gassman considers the cases in which the space between the spheres is empty and in which it is filled with fluid. These correspond to dry and totally saturated samples. In the dry system the velocity in a particular direction varies as the sixth root of the pressure implying zero velocity at zero pressure. The velocity in the wet system is a more complicated function of pressure which is not zero at zero pressure and which rises very slightly with increasing pressure. The velocity in the wet system is higher at any pressure than the velocity in the dry system.

The experimental results reported here show a certain agreement with the behavior of the model. In both wet and dry samples the shapes of the curves are similar to the theoretical ones; i.e., the dry curve shows a large increase with pressure and is concave downward while the saturated curve is nearly flat. At low pressures the dry velocity varies approximately as the sixth root of the pressure. With a real sandstone containing some sort of cementing material one would not expect the velocity to approach zero at zero pressure yet our experimental results do not rule out this possibility. In the saturated case the experimental curve, while similar in shape to that predicted by the model, does not remain above the dry curve. The actual velocity in the dry sandstone probably increases more at large pressures than that of the model due to the decrease of pore space.

The writers wish to thank the Sun Company for furnishing Samples 46 and 48 and the Magnolia Company for Samples 52 and 53.

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ADDENDUM

Dr. H. C. Dunlap of the Atlantic Refining Company, in discussing our paper at the Los Angeles meeting, suggested that the point at which added water no longer increases the velocity might be associated with the irreducible water content of the core and offered to determine this on Core 188 for which we had complete data. His results are quoted herewith.

"We cut the core you submitted to us into three pieces; A (2.45 cm long), B (2.50 cm long), and C (1.33 cm long), which were run to connate water in the high speed centrifuge. The displacing phase was oil, and the pressure difference between the phases was 200 psi. This pressure was maintained for one hour. Data obtained are shown below:

Core No.	*Percent porosity*	*Percent connate water*
A	13.4	18.8
B	8.0	20.2
C	14.1	19.1

The data given on this core in your Figure 8, where velocity is plotted against water saturation at various pressures, indicates that a value of about 19 percent might well be the point at which velocity increase begins to fall off as the water saturation is decreased. To be sure of this would require more determinations of velocity as a function of saturation in this region than are given in Figure 8. However, if increase in percent water serves to increase velocity in the low saturation region by providing better acoustic coupling between rock particles, it is not unreasonable to expect that the water saturation at which the water begins to be mobile may have some significance. Water saturations less than this value for all practical purposes might be regarded as equivalent to a cementing material, since it is rigidly bound to the rock.

Although one case obviously proves nothing, I think it might be interesting to investigate this point further if you plan to do additional work on velocity or attenuation *vs* saturation relationships."

D. S. HUGHES

HIGH MAGNETIC EFFECT OF LATERITIC SOIL IN CUBA

PAUL M. TUCKER*

ABSTRACT

During the course of a conventional vertical magnetic survey in Cuba, it was found that many stations underlain by lateritic red soil gave unusually erratic values. A susceptibility determination of the soil showed it to have a value of $2{,}800 \times 10^{-6}$ cgs.

INTRODUCTION

The island of Cuba is rather unusual in having distillate accumulations in fractures of serpentine. The Standard Oil Company of Cuba in 1944–45 covered the serpentine belt of the island with a conventional vertical magnetic survey in order to determine areas of serpentine under cover at shallow depths. During the course of the survey it was noticed that a great variation in value was common on repeat readings of many magnetometer stations. Magnetic storms were suspected during the readings but were eliminated as a cause when a check was made at the base station. A faulty instrument was not the cause, as normal ties and checks were made in adjacent areas. The discrepancy seemed to result from some local variation at the anomalous stations.

EXPERIMENTAL DATA

An experimental line was run in the vicinity of one of the erratic stations, the results of which are shown on Figure 1. A maximum difference of over 750 gammas occurred in 15 meters, which would indicate a highly magnetic condition very near the surface.

The area in question is underlain by a Miocene limestone, covered in part by a red soil, the weathered product of the limestone. The occurrence of the red soil, a laterite, is not an uncommon phenomenon for tropical countries. According to Lindgren ("Mineral Deposits," 1933): "In tropical countries the deep residual soil . . . very often is essentially a mixture of the hydroxides of iron and aluminum. The laterite may be derived from any igneous or sedimentary rock but serpentine and limestone are especially favorable." The processes in their formation are not clear but " . . . it is now generally conceded that this is caused simply by the long continued action of ordinary ground-waters under special conditions of moisture and heat."

That the red soil was highly magnetic could readily be seen. A small magnet run through the soil accumulated an appreciable quantity of dust on the poles of the magnet.

Samples of the red soil taken from the station at 15 meters were sent to Dr.

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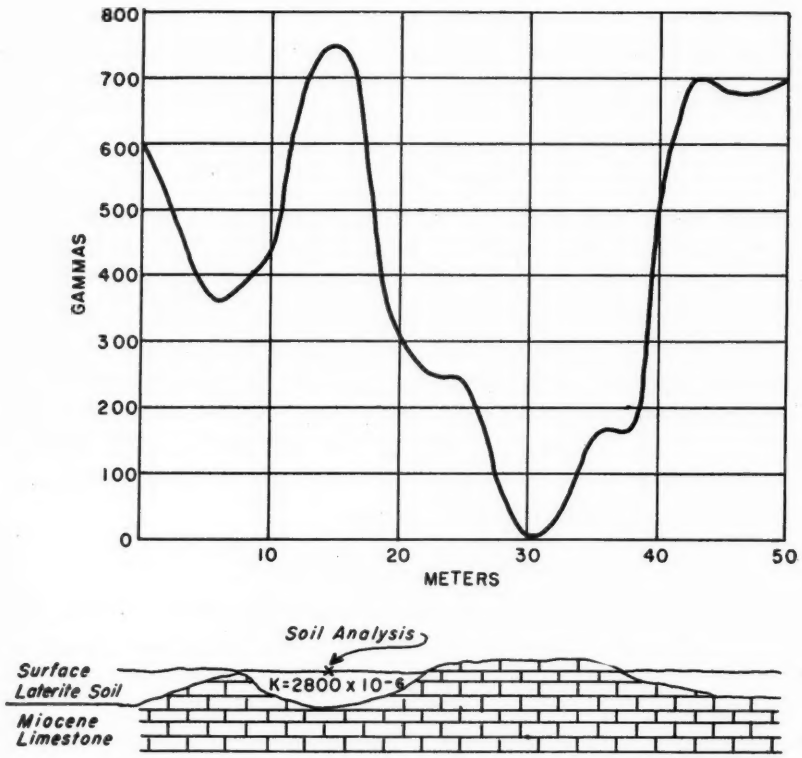
R. J. Watson of The Carter Oil Company, in Tulsa, Oklahoma, for susceptibility determinations. He found the susceptibility to be about $2{,}800 \times 10^{-6}$ cgs, a rather large value for "soil." A test of the remanent magnetism indicated a value of $3{,}600 \times 10^{-6}$ cgs.



MAGNETIC PROFILE
and
SURFACE OUTCROPS

30 KM SE OF HAVANA, CUBA.

FIG. 1

INTERPRETATION OF THE DATA

The short profile of Figure 1 shows increasing vertical magnetic intensity values from an arbitrary value of zero over the outcrop of limestone, to rather high values (over 600 gammas) on the flanking soil covered areas. The profile indicates two possible orders of effects:

1) a relatively broad minimum effect of 50 meters (the length of the profile) or greater width, and

2) superimposed on the left flank of this minimum is a maximum of approximately 440 gammas relief. This narrow anomaly may be considered as having a positive effect of approximately 360 gammas and two negative effects of approximately 80 gammas each.

An anomaly such as is suggested in effect (2) may be attributed to a layer of magnetic material of very shallow depth. This is indicated in the sharpness of the anomaly. If we consider the curve representative of a horizontal cylinder, which it approximates, the maximum depth of such a body would be 6 meters. By using the determined susceptibility of 2800×10^{-6} cgs, the depth may be computed to be less than one meter. The surface profile shown on Figure 1 is an average of these two values.

CONCLUSIONS

A rather surprisingly large magnetic susceptibility value of $2{,}800 \times 10^{-6}$ cgs was found for the lateritic red soil in a selected locality in Cuba. The magnetic measurements over such a soil by a land-type meter will be clouded by erratic values due to varying thicknesses of the highly magnetic soil.

By a judicious location of stations, and a multiple number of closely spaced readings, the local effect of the soil may be disentangled. However, these effects would cancel themselves if the readings were obtained at a greater height. This could be most readily obtained by the airborne magnetometer.

ACKNOWLEDGEMENT

The author expresses his appreciation to the Standard Oil Company (N. J.) for permitting the use of Company files in preparing this paper and for permitting the publication of the data.

THREE DIMENSIONAL INTERPRETATION OF GRAVITATIONAL ANOMALIES, PART II*

FRASER S. GRANT†

ABSTRACT

This is the second of two papers describing a method of interpreting residual gravitational anomalies in terms of three-dimensional geological structures. This paper describes an analytical method for smoothing the data, and for constructing charts and templates for computing derivatives and other quantities required in the interpretation formulae already given in Part I. Tables of all quantities required for the practical utilization of this procedure are provided. Two examples of the application of these methods are given: the first, an artificial problem, and the second, an actual survey conducted over a sulphide body that has been outlined by extensive drilling.

1. ON SMOOTHING THE RESIDUAL FIELD

In a geophysical gravity survey, the data are measured by physical instruments and frequently are subjected to elaborate reductions; consequently they are not exact and are seldom very precise. Nor, since they are acquired at a discrete set of points, are they complete; they give only a more or less approximate picture of the behaviour of a field of force. Obviously no values however unlikely can be excluded positively at points between stations as being inconsistent with the data; all that can be supposed is that intermediate "peaks" and "valleys" are unlikely, and, if they do exist, they must have their origin in very shallow disturbances which in any event ought to be disregarded. As a result, contours are sketched in by interpolating between station values, and profiles are tacitly assumed to be the simplest curves that can be drawn through sets of datum points. Thus the field is to some extent artificially smoothed in the process of contouring.

Nevertheless, there remains an inherent lack of determinacy which affects the data with a spurious sort of irregularity, frequently putting kinks and wobbles in the contour lines. Thus if one is inclined to think of the distribution of gravity residues (which are designated with the symbol g) as defining a mathematical surface, "anomalies" would make their appearance as humps which are often pocked and corrugated in an irregular way. The causes of these disturbances are various and cannot easily be determined; they may originate in the near-surface inhomogeneity of the country rock, for example, or in faulty reduction of the original data, or simply in mistakes—either in observation or in arithmetic. The phenomenal effects due to such causes are of course indistinguishable, but they are usually independent of one another—that is, they are usually random;

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and often they are very local in extent, individually affecting only a single station.

It is acknowledged that direct interpretation methods aim at finding geometrically simple structures to account for given residual anomalies. Such structures, however, produce fields which are smooth and regular; and so in order to establish a realistic connection between geophysical phenomena and formulae which are based upon such simple fields, a smoothed version of the observed field must be sought.

2. AN ANALYTICAL METHOD OF SMOOTHING

The smoothing may be performed by means of the transform

$$\bar{g}(x, y) = \frac{\beta}{\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g(u, v) e^{-\beta[(x-u)^2+(y-v)^2]} du dv \tag{1}$$

which has previously been employed for this purpose by Bullard and Cooper (1948).

The mechanism of the smoothing process may be explained briefly. We may begin by writing

$$g(x, y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g(u, v) \delta(x - u) \delta(y - v) du dv$$

where the Dirac δ-function is defined by the following set of properties: (see, e.g., Rojansky, §12)

$$\begin{aligned} &= 0 && x \leqq u \\ \delta(x - u) &= 1/\epsilon && u < x < u + \epsilon, \quad \epsilon \to 0 \\ &= 0 && x \geqq u + \epsilon \end{aligned}$$

and

$$\int_{-\infty}^{\infty} \delta(x - u) du = 1.$$

One representation that is consistent with this definition is

$$\delta(x - u) = \lim_{\beta \to \infty} \sqrt{\beta/\pi}\, e^{-\beta(x-u)^2},$$

and so

$$g(x, y) = \lim_{\beta \to \infty} \beta/\pi \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g(u, v) e^{-\beta[(x-u)^2+(y-v)^2]} du dv. \tag{2}$$

Expression (1) is clearly tantamount to weighting each observed value of g with the joint normal distribution in x and y of the variables u and v respectively (assuming the same *a priori* probability of error in both cases), and taking the average over the whole field. The effect of this is to give more or less large statistical weight, according to the value of β, to values of g recorded within the im-

mediate vicinity of x and y, and decreasing weight to values recorded at more remote points. This process takes into account random fluctuations of g from its median value which fall within the normal error curve. As β is allowed to increase, the normal distribution surface becomes more sharply peaked, and the influence of the observations taken at or very near to (x, y) is heightened; until finally, as equation (2) shows, when $\beta \to \infty$ a statistical weight of unity is attached to the value of g at (x, y) and zero everywhere else. With suitable values of β, this averaging process will have very little effect upon slowly-varying functions $g(u, v)$, but will severely iron out small, sharp fluctuations. Suppose, for example that $g(u, v)$ can be written as a double Fourier series whose general term is

$$g_{mn}(u, v) = A_{mn} \cos mu \cos nv.$$

Then it follows from (1) that

$$\bar{g}_{mn} = A_{mn} e^{-m^2+n^2/4\beta}$$

and so a proper choice of β will make all but a preassigned number of harmonic terms in the smoothed field negligibly small.

The Potential U of Part I may now be defined through the identification of its downward normal gradient over the ground plane, $-U_{z_0}(x, y)$, with the smoothed residual gravity field $\bar{g}(x, y)$ at each point (x, y). The formulae (I, 20) for finding the position of the centre of gravity of V from the map of the residual field may then be justified if it can be shown that

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}(x + iy)\bar{g}(x, y)dxdy = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}(x + iy)g(x, y)dxdy$$

and

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\bar{g}(x, y)dxdy = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}g(x, y)dxdy.$$

The proofs require only a single line; they will be left to the reader.

3. CALCULATION OF THE DERIVATIVES OF U

Calculation of the derivatives of the smoothed field at the position on the ground of the centre of gravity of V, which are required by the formulae (I, 11)–(I, 16), rests upon two theorems: one (A) due to Kosbahn (1949), and the other (B) to Kreisel (1949).

Theorem A. The potential U due to a distribution of mass lying below the horizontal plane $z = 0$ has, at any point $P(\xi, \eta, \zeta)$ above this plane, the alternative expressions

$$U_p(\xi, \eta, \zeta) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{U_z(x, y)dxdy}{[(\xi - x)^2 + (\eta - y)^2 + \zeta^2]^{1/2}} \tag{3}$$

and

$$U_p(\xi, \eta, \zeta) = \frac{\zeta}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{U(x, y)dxdy}{[(\xi - x)^2 + (\eta - y)^2 + \zeta^2]^{3/2}} \tag{4}$$

in which $U(x, y)$ and $U_z(x, y)$ are defined on $z=0$, and which are, respectively, even and odd functions of ζ.

Theorem B.

$$k(x_1, \cdots, x_n) = \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} \psi(\xi_1, \cdots, \xi_n) L(x_1 - \xi_1, \cdots, \xi_n - \xi_n; \alpha) d\xi_1 \cdots d\xi_n \quad (5)$$

is a type of integral equation in which k is known from measurement, L is a given kernel, and ψ is to be determined. Since rapidly-oscillating ψ have small k, and sinze measurements of k are necessarily undertain within non-zero limits of experimental error, very different ψ are consistent with any given set of measured values of k. Thus ψ is not determined continuously by measurements of k, and hence cannot be determined by (5), unless it is a slowly-varying or "smooth" function. If ψ itself is not smooth, it may be smoothed analytically by means of the transform

$$\bar{\psi}(x_1, \cdots, x_n) = \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} \psi(u_1, \cdots, u_n) \mu(x_1 - u_1, \cdots, x_n - u_n) du_1 \cdots du_n$$

where μ is a normalized smoothing function, so that

$$\int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} \mu(x_1, \cdots, x_n) dx_1 \cdots dx_n = 1.$$

The Theorem is: if Λ and M are the Fourier transforms of L and μ, respectively, and if

$$\lambda(x_1, \cdots, x_n) = \frac{1}{(2\pi)^n} \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} \frac{M(p_1, \cdots, \phi_n)}{\Lambda(\phi_1, \cdots, \phi_n)} e^{i(p_1 x_1 + \cdots + p_n x_n)} d\phi_1 \cdots dp_n$$

is bounded and integrable, then, subject to conditions on L, M, and ψ (which are always fulfilled in geophysics) set forth by Kreisel,

$$\bar{\psi}(x_1, \cdots, x_n) = \int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} k(\xi_1, \cdots, \xi_n) \lambda(x_1 - \xi_1, \cdots, x_n - \xi_n) d\xi_1 \cdots d\xi_n \quad (6)$$

and $\bar{\psi}$ is determined continuously by k.

The gravitational field at the point (ξ, η) on the ground plane (which we may take to be $z=0$) due to a gravitational field $g(x, y)_z$ at a level z below this plane is

$$g(\xi, \eta)_0 = \frac{z}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{g(x, y)_z dx dy}{[(\xi - x)^2 + (\eta - y)^2 + z^2]^{3/2}}. \quad (7)$$

This integral equation is of the type (5) and the conditions for the applicability

of Kreisel's theorem are satisfied by the functions involved. The smoothing function μ is prescribed in (1), viz:

$$\mu(x, y) = (\beta/\pi)e^{-\beta(x^2+y^2)}$$

so that

$$M(p_1, p_2) = \beta/2\pi^2 \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} e^{-\beta(x^2+y^2)+i(p_1x+p_2y)}dxdy = (2\pi)^{-1}e^{-p_1^2+p_2^2/4\beta}.$$

The following derivation of Λ has been given by Kreisel:

$$\Lambda(p_1, p_2) = \frac{z}{(2\pi)^2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{e^{i(p_1x+p_2y)}}{(x^2+y^2+z^2)^{3/2}}dxdy.$$

Rotate the axes so that $p_1x+p_2y=x'\sqrt{p_1^2+p_2^2}$, $-p_2x+p_1y=y'\sqrt{p_1^2+p_2^2}$, and then change to polar coördinates $x'+iy'=re^{i\theta}$

$$\Lambda(p_1, p_2) = \frac{z}{(2\pi)^2}\int_0^{\infty}\frac{rdr}{(r^2+z^2)^{3/2}}\int_0^{2\pi} e^{-ir\sqrt{p_1^2+p_2^2}\cos\theta}\,d\theta.$$

$$= z/2\pi\int_0^{\infty} J_0(r\sqrt{p_1^2+p_2^2})(r^2+z^2)^{-3/2}rdr.$$

This is an integral of Hankel's type. It may be integrated by Lerch's method (Watson, p. 434) and reduced to

$$\Lambda(p_1, p_2) = (2\pi)^{-1}e^{-z\sqrt{p_1^2+p_2^2}}.$$

Therefore

$$\lambda(x, y) = (2\pi)^{-2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} e^{-p_1^2+p_2^2/4\beta+z\sqrt{p_1^2+p_2^2}}e^{i(p_1x+p_2y)}dp_1dp_2,$$

which, under a rotation of the axes as before, becomes

$$\lambda(x, y) = 1/2\pi\int_{-\infty}^{\infty} e^{-u^2/4\beta+uz}J_0(u\sqrt{x^2+y^2})udu.$$

The smoothed field at depth z below the ground is, according to (6)

$$-U_z \equiv g(x, y)_z = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} g(\xi, \eta)_0\lambda(x-\xi, y-\eta)d\xi d\eta,$$

which, in polar coordinates $x+iy=re^{i\theta}$ and $\xi+i\eta=\rho e^{i\phi}$, is

$$\bar{g}(r, \theta)_z = (2\pi)^{-1}\int_0^{\infty}\int_0^{2\pi}\int_0^{\infty} g(\rho, \phi)_0 e^{-u^2/4\beta+uz}$$

$$\cdot J_0(u\sqrt{r^2+\rho^2-2r\rho\cos(\theta-\phi)})u\rho du d\phi d\rho.$$

$$= (2\pi)^{-1}\sum_{n=-\infty}^{n=\infty}\int_0^{\infty}\int_0^{2\pi}\int_0^{\infty} g(\rho, \phi)_0 e^{-u^2/4\beta+uz}$$

$$\cdot J_n(ur)J_n(u\rho)\cos n(\theta-\phi)u\rho du d\phi d\rho \qquad (8)$$

in consequence of the Neumann addition theorem. Allowing $z \to 0$ gives for the smoothed residual gravity field

$$-U_{zr} \equiv \bar{g}(r, \theta) = (2\pi)^{-1} \sum_{n=-\infty}^{n=\infty} \int_0^\infty \int_0^{2\pi} \int_0^\infty g(\rho, \phi) e^{-u^2/4\beta} \cdot J_n(ur) J_n(u\rho) \cos n(\theta - \phi) u\rho du d\phi d\rho \qquad (9)$$

Also, since

$$U(x, y, z) = \int_{-\infty}^{z} U_z(x, y, z) dz,$$

$$U(r, \theta) = (2\pi)^{-1} \sum_{n=-\infty}^{n=\infty} \int_0^\infty \int_0^{2\pi} \int_0^\infty g(\rho, \phi) e^{-u^2/4\beta} \cdot J_n(ur) J_n(u\rho) \cos n(\theta - \phi) \rho du d\phi d\rho \qquad (10)$$

from (8).

Equations (3), (4), (9), and (10) collectively furnish the tools necessary for the calculation of all of the derivatives of the smoothed field directly from the data: Even derivatives of z may be determined through (3) and (9); odd derivatives of z through (4) and (10). For illustration, an example of each kind will be demonstrated in detail.

I. Even derivatives of z: e.g., U_x^0.

From (3),

$$U_\xi(\xi, \eta, \zeta) = -\frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{(\xi - x) U_z(x, y) dx dy}{[(\xi - x)^2 + (\eta - y)^2 + \zeta^2]^{3/2}}.$$

If the origin of the coördinates be transposed to lie directly over the centre of gravity of the anomalous body (§8, Part I), the derivatives there are identically the quantities designated in Part I with the superscript ^{0}. That is,

$$U_x^0 \equiv U_\xi(0) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{U_z(x, y) x dx dy}{(x^2 + y^2)^{3/2}}$$

or, in polar coordinates $x + iy = re^{i\theta}$,

$$U_x^0 = (1/2\pi) \int_0^\infty \int_0^{2\pi} U_{z_0}(r, \theta) \cos \theta (1/r) d\theta dr. \qquad (11)$$

Substitution of (9) into this integral gives

$$U_x^0 = (4\pi^2)^{-1} \sum_{n=-\infty}^{n=\infty} \int_0^\infty \int_0^{2\pi} g(\rho, \phi) \rho d\phi d\rho \int_0^\infty e^{-u^2/4\beta} J_n(u\rho) u du \cdot \int_0^\infty J_n(ur)(1/r) dr \int_0^{2\pi} \cos n(\theta - \phi) \cos \theta d\theta.$$

The changes in the order of the integrations are warranted by the absolute convergence of the integral.

Integration with respect to θ removes all terms except that in which $n=1$. The r-integral can then be identified with the Weber-Schäfheitlin-Sonine integral (Watson, p. 391) with a suitable change of the independent variable, giving

$$U_x{}^0 = (8\pi)^{-1}\int_0^\infty\int_0^{2\pi} g(\rho, \phi)\cos\phi\rho d\phi d\rho\int_0^\infty e^{-u^2/4\beta}J_1(u\rho)udu.$$

The u-integration may be performed through Hankel's integral (Watson, p. 394) using Kummer's first transform, and so finally

$$U_x{}^0 = \int_0^\infty\int_0^{2\pi} g(\rho, \phi)\Lambda^{(ii)}(\rho)\cos\phi d\phi d\rho, \tag{12}$$

where

$$\Lambda^{(ii)}(\rho) = \beta^{3/2}(8\pi^{1/2})^{-1}e^{-\beta\rho^2}{}_1F_1(\tfrac{1}{2};\ 2;\ \beta\rho^2),$$

and where ${}_1F_1$ denotes the confluent hypergeometric function in the notation of Pochammer.

II. Odd derivatives of z: e.g., $U_{zz}{}^0$.

Form (4),

$$U_{zx}{}^0 \equiv U_{\zeta\xi}(0) = -(3/2\pi)\int_0^\infty\int_0^{2\pi} U(r, \theta)\cos\theta(1/r^3)d\theta dr. \tag{13}$$

Substitution of (10) into this expression gives

$$U_{zz}{}^0 = -(3/4\pi^2)\sum_{n=-\infty}^{n=\infty}\int_0^\infty\int_0^{2\pi} g(\rho, \phi)\rho d\phi d\rho\int_0^\infty e^{-u^2/4\beta}J_n(u\rho)du$$
$$\cdot\int_0^\infty J_n(ur)(1/r^3)dr\int_0^{2\pi}\cos n(\theta-\phi)\cos\theta d\theta.$$

As before, integration with respect to θ removes all terms except that in which $n=1$, and the r-integration may then be performed through the Weber-Schäfheitlin-Sonine integral, giving

$$U_{zz}{}^0 = (1/4\pi)\int_0^\infty\int_0^{2\pi} g(\rho, \phi)\cos\phi\rho d\phi d\rho\int_0^\infty e^{-u^2/4\beta}J_1(u\rho)u^2du.$$

The u-integral may be identified with Weber's first exponential integral, and so

$$U_{zz}{}^0 = \int_0^\infty\int_0^{2\pi} g(\rho, \phi)\Lambda^{(iv)}(\rho)\cos\phi d\phi dp, \tag{14}$$

where

$$\Lambda^{(\mathrm{iv})}(\rho) = \beta^2\pi^{-1}e^{-\beta\rho^2}\cdot\rho^2.$$

The other derivatives, which may be found in a like manner, are as follows:

$$U_z^0 = \int_0^\infty g(\rho)\Lambda^{(\mathrm{iii})}(\rho)d\rho,$$

where

$$\Lambda^{(\mathrm{iii})}(\rho) = 2\beta e^{-\beta\rho^2}\cdot\rho \quad \text{and} \quad g(\rho) = \frac{1}{2\pi}\int_0^{2\pi} g(\rho, \phi)d\phi$$

$$U_{zz}^0 = \int_0^\infty g(\rho)\Lambda^{(\mathrm{v})}(\rho)d\rho,$$

where

$$\Lambda^{(\mathrm{v})}(\rho) = 2\pi^{1/2}\beta^{3/2}e^{-\beta\rho^2}{}_1F_1(-\tfrac{1}{2};\ 1;\ \beta\rho^2)\cdot\rho$$

$$U_{xx}^0 = -\frac{1}{2}\int_0^\infty g(\rho)\Lambda^{(\mathrm{v})}(\rho)d\rho + \int_0^\infty\int_0^{2\pi} g(\rho, \phi)\Lambda^{(\mathrm{vi})}(\rho)\cos 2\phi d\phi d\rho,$$

where

$$\Lambda^{(\mathrm{vi})}(\rho) = 3/16\cdot\pi^{-1/2}\beta^{5/2}e^{-\beta\rho^2}{}_1F_1(\tfrac{1}{2};\ 3;\ \beta\rho^2)\rho^3$$

$$U_{zzz}^0 = \int_0^\infty\int_0^{2\pi} g(\rho, \phi)\Lambda^{(\mathrm{vii})}(\rho)\cos\phi d\phi d\rho,$$

where

$$\Lambda^{(\mathrm{vii})}(\rho) = 3/2\pi^{-1/2}\beta^{5/2}e^{-\beta\rho^2}{}_1F_1(-\tfrac{1}{2};\ 2;\ \beta\rho^2)\rho^2. \qquad (15)$$

$$U_{zzx}^0 = -\frac{1}{2}\int_0^\infty g(\rho)\Lambda^{(x)}(\rho)d\rho + \int_0^\infty\int_0^{2\pi} g(\rho, \phi)\Lambda^{(\mathrm{viii})}(\rho)\cos 2\phi d\phi d\rho,$$

where

$$\Lambda^{(\mathrm{viii})}(\rho) = \pi^{-1}\beta^2e^{-\beta\rho^2}\cdot\rho^3.$$

$$U_{xxx}^0 = -\frac{3}{4}\int_0^\infty\int_0^{2\pi} g(\rho, \phi)\Lambda^{(\mathrm{viii})}(\rho)\cos\phi d\phi d\rho + \int_0^\infty\int_0^{2\pi} g(\rho, \phi)\Lambda^{(\mathrm{ix})}(\rho)\cos 3\phi d\phi d\rho,$$

where

$$\Lambda^{(\mathrm{ix})}(\rho) = 5/32\pi^{-1/2}\beta^{7/2}e^{-\beta\rho^2}{}_1F_1(\tfrac{1}{2};\ 4;\ \beta\rho^2)\rho^4.$$

$$U_{zzz}^0 = \int_0^\infty g(\rho)\Lambda^{(x)}(\rho)d\rho,$$

where

$$\Lambda^{(x)}(\rho) = 4\beta^2e^{-\beta\rho^2}{}_1F_1(-1;\ 1;\ \beta\rho^2)\rho.$$

4. TABULATION OF THE WEIGHTING FUNCTIONS

The radial weighting functions $\Lambda(\rho)$ may be made nondimensional by expressing ρ in units of s, the mesh side if the net is square, or an average station-spacing if it is not. β will then be replaced with $\tau=\beta S^2$, otherwise the forms of these functions remain unchanged but for the inclusion of a dimensional factor. They have been tabulated for $\tau=1$ from the tables of the confluent hypergeometric function (British Association, Leeds, 1927) and are shown graphically in Figure 1. These tables cover quite thoroughly the range $0 \leqq \rho_{1z} \leqq 8$, but in most cases it was necessary to extend the computations somewhat beyond this limit. To do so, an asymptotic form was used.

$$e^{-\rho_1^2}{}_1F_1(\alpha;\ \gamma;\ \rho_1^2) \cong (\Gamma(\gamma)/\Gamma(\alpha))\rho_1^{2(\alpha-\gamma)}\left\{1 + \frac{(1-\alpha)(\gamma-\alpha)}{\rho_1^2} + \frac{(1-\alpha)(2-\alpha)(\gamma-\alpha)(\gamma-\alpha+1)}{2!\rho_1^4} + \cdots\right\}. \qquad (16)$$

The first part of the complete asymptotic expansion for ${}_1F_1$ (Jeffreys & Jeffreys, p. 610) becomes negligible for $\rho_1^2 > 8$; hence (16).

The computations of Table I, in which $L(r_1) = \int_0^{r_1}\Lambda(\rho_1)d\rho_1$, have been carried out from the tabulated entries for $\Lambda(\rho_1)$ according to Weddle's Rule, while the asymptotic values for $r_1^2 > 8$ were computed from the following formulae, which give values accurate to four places of decimals:

$$L^{(ii)}(r_1) = 0.189 + .07951nr_1 - .0298/r_1^2 - .0280/r_1^4 - .0543/r_1^6.$$

$$L^{(v)}(r_1) = 0.287 + .250/r_1 + .187/r_1^3 + .352/r_1^5.$$

$$L^{(vi)}(r_1) = 0.377 - .750/r_1 - .312/r_1^3 - .492/r_1^5.$$

$$L^{(ix)}(r_1) = 0.306 - .938/r_1^2 - 2.462/r_1^4 - 1.846/r_1^6.$$

Table II has been built up by direct integration.

It is necessary in order to cover all problems, to have these results available for a number of values of τ other than 1. Tables for any value of τ may be made up very readily from those for $\tau=1$ as follows. Consider, as an example, the function

$$\Lambda^{(v)}(\rho_1) = s^{-1}\pi^{-1/2}\tau^{3/2}e^{-\tau\rho_1^2}{}_1F_1(-\tfrac{1}{2};\ 1;\ \tau\rho_1^2)\rho_1, \qquad \rho_1 = \rho/s$$

given here in its non-dimensional form.

The function

$$L^{(v)}(r_{10})_{\tau=1} = \int_0^{r_{10}} \Lambda^{(v)}(\rho_{10})_{\tau=1}d\rho_1,$$

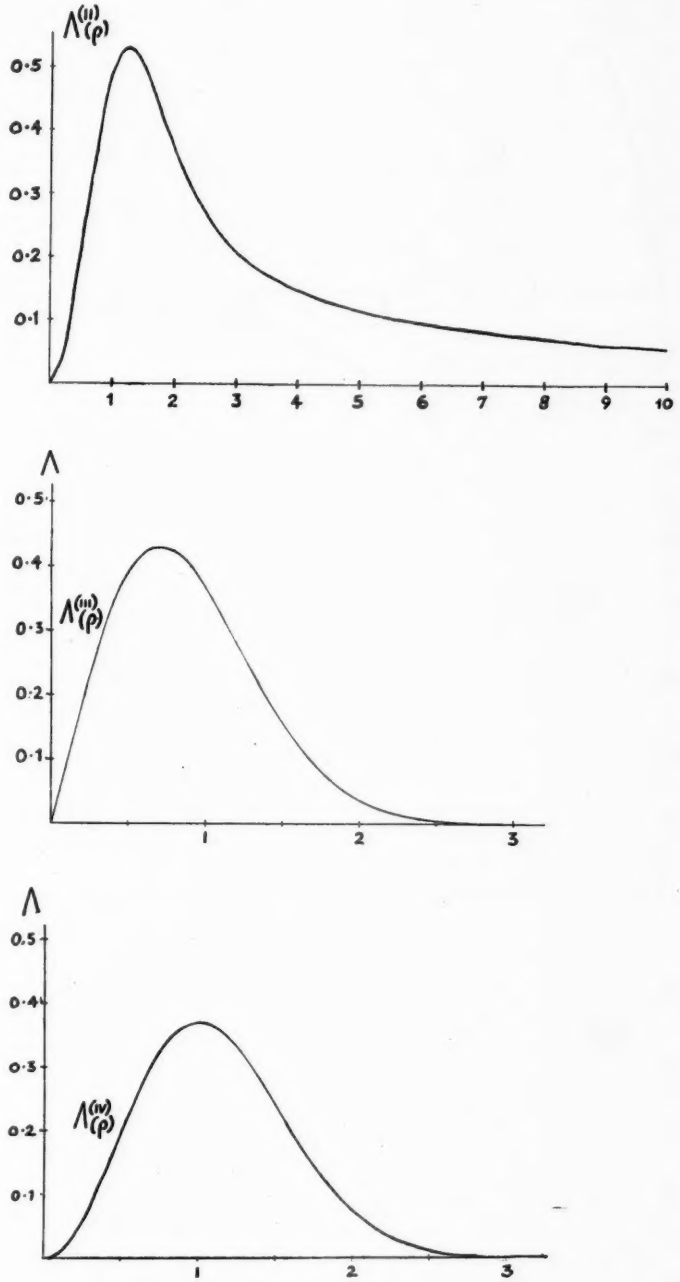

FIG. 1. The Weighting Functions $\Lambda(\rho)$.

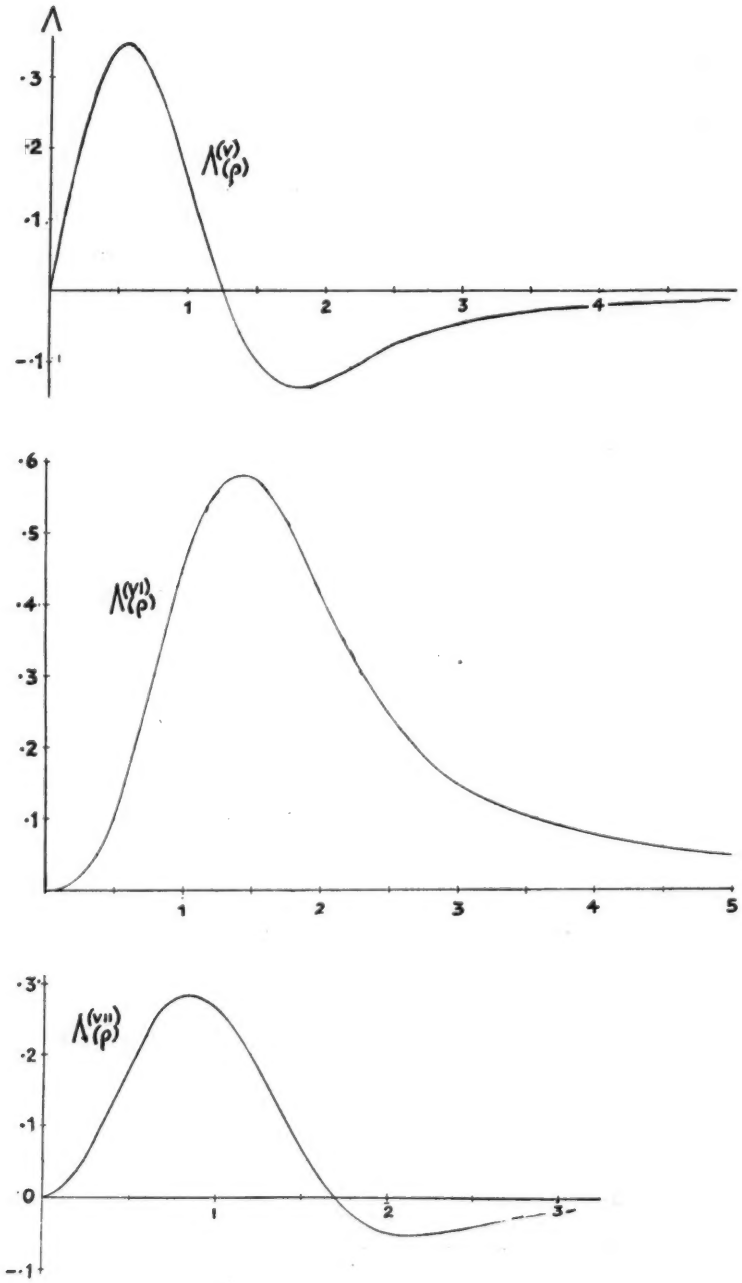

FIG. 1—*continued*

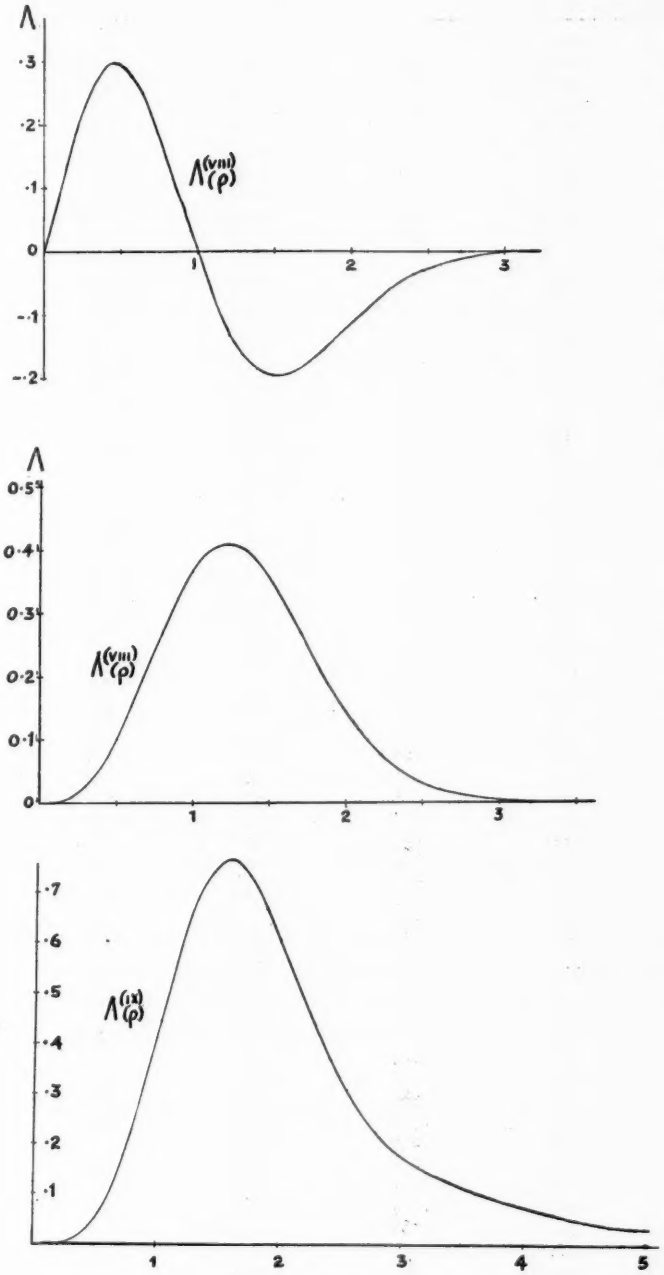

FIG. 1—*continued*

TABLE I
ASYMPTOTIC VALUES

r_1	$L^{(ii)}r_1$	$L^{(v)}r_1$	$L^{(vi)}r_1$	$L^{(vii)}r_1$	$L^{(ix)}r_1$
0.000	.000	.000	.000	.000	.000
0.141	.000206	.0349	.0000104	.00122	.0000017
0.200	.000686	.0688	.000041	.0041	.0000085
0.245	.00130	.102	.000092	.0076	.0000227
0.283	.00200	.134	.000162	.0118	.000052
0.316	.00280	.164	.000250	.0163	.000079
0.346	.00368	.194	.000341	.0213	.000122
0.387	.00598	.238	.000551	.0289	.000210
0.447	.00948	.305	.000948	.0429	.000421
0.500	.01320	.369	.00144	.0529	.00071
0.548	.0171	.424	.00202	.0735	.00108
0.592	.0204	.480	.00268	.0897	.00155
0.632	.0236	.528	.00341	.106	.00204
0.671	.0270	.572	.00420	.122	.00272
0.707	.0304	.616	.00505	.138	.00344
0.742	.0338	.652	.00592	.153	.00425
0.774	.0374	.688	.00690	.169	.00511
0.806	.0410	.713	.00788	.184	.00606
0.837	.0444	.748	.00888	.198	.00707
0.866	.0480	.772	.00996	.212	.00819
0.894	.0514	.796	.0111	.226	.00931
0.922	.0550	.816	.0118	.238	.0105
0.948	.0586	.836	.0133	.251	.0118
0.975	.0620	.852	.0144	.263	.0131
1.000	.0656	.868	.0156	.275	.0145
1.049	.0724	.894	.0180	.297	.0174
1.095	.0790	.908	.0204	.316	.0204
1.140	.0854	.920	.0228	.334	.0235
1.183	.0918	.932	.0252	.350	.0267
1.225	.0980	.936	.0276	.363	.0301
1.265	.1040	.936	.0299	.376	.0334
1.304	.1098	.932	.0322	.388	.0370
1.342	.1154	.928	.0346	.394	.0403
1.378	.121	.920	.0368	.404	.0439
1.414	.126	.913	.0390	.410	.0472
1.483	.136	.888	.0431	.420	.0539
1.549	.145	.860	.0471	.429	.0606
1.612	.154	.832	.0510	.432	.0671
1.673	.162	.800	.0545	.436	.0730
1.732	.165	.776	.0578	.436	.0790
1.871	.186	.708	.0651	.429	.0922
2.000	.200	.648	.0721	.420	.1032
2.121	.212	.592	.0763	.410	.1127
2.236	.224	.548	.0806	.401	.1204
2.345	.232	.508	.0842	.391	.1270
2.449	.240	.476	.0873	.382	.1321
2.549	.248	.448	.0898	.376	.1368
2.646	.256	.424	.0922	.369	.1404
2.739	.262	.404	.0941	.366	.1437
2.828	.268	.386	.0959	.359	.1462
3.0	.273	.358	.0988	.353	.1516
3.5	.287	.297	.1053		.1618
4.0	.298	.255	.1100	.337	.1678
4.5	.308	.224	.1136		.1716
5.0	.316	.197	.1164	.330	.1742
6.0	.331	.162	.1206		.1775
7.0	.344	.137	.1235		.1794
8.0	.354	.118	.1257		
9.0	.364	.104	.1274		
10.0	.372	.092	.1287	.322	
11.0	.380		.1299		
12.0	.386		.1307		
13.0	.393				
20.0		.042	.1349		
∞		.000	.1403	.320	.1842

TABLE II

r_1	$L^{(iii)}(r_1)$	$L^{(iv)}(r_1)$	$L^{(vi)}(r^1)$	$L^{(viii)}(r^1)$
0.0	0.00000	.000	0.000	.000
.1	0.010	.00021	0.020	.000008
.2	0.039	.00166	0.077	.00011
.3	0.086	.00543	0.165	.00061
.4	0.148	.0123	0.273	.00183
.5	0.221	.0228	0.389	.00431
.6	0.302	.0371	0.502	.00821
.7	0.387	.0547	0.600	.0139
.8	0.473	.0750	0.675	.0216
.9	0.555	.0974	0.721	.0301
1.0	0.632	.121	0.736	.0421
1.1	0.702	.144	0.722	.0545
1.2	0.763	.166	0.682	.0671
1.3	0.815	.187	0.624	.0803
1.4	0.859	.209	0.552	.0929
1.5	0.895	.222	0.474	.1048
1.6	0.923	.236	0.394	.1152
1.7	0.944	.247	0.321	.1248
1.8	0.961	.256	0.254	.1327
1.9	0.973	.264	0.195	.1392
2.0	0.982	.269	0.147	.1445
2.1	0.988	.273	0.107	.1486
2.2	0.992	.276	0.077	.1518
2.3	0.995	.278	0.053	.1540
2.4	0.997	.279	0.046	.1568
2.5	0.998	.280	0.024	.1569
2.6	0.999	.281	0.016	.1578
2.7	0.999	.281	0.020	.1581
2.8	1.000	.282	0.006	.1585
2.9	1.000	.282	0.004	.1588
3.0	1.000	.282	0.002	.1590

which we shall denote with a new symbol

$$\mathcal{L}^{(v)}(r_{10}) = \int_0^{r_{10}} \lambda^{(v)}(\rho_{10})d\rho_{10}$$

has been tabulated for a sequence of particular values of r_1 (the square roots of the arguments used in the B.A.A.S. Tables) which are designated above as r_{10}. These entries have been obtained by the numerical integration of $\lambda^{(v)}(\rho_{10})$, which in turn has been tabulated for identically the same particular values ρ_{10} of ρ_1. Now

$$\lambda^{(v)}(\rho_{10}) = s^{-1}\pi^{-1/2}e^{-\rho_{10}^2}{}_1F_1(-\tfrac{1}{2}; 1; \rho_{10}^2)\rho_{10}$$

and so

$$\lambda^{(v)}(\sqrt{\tau}\rho) = \tau^{-1}\Lambda^{(v)}(\rho_1).$$

Therefore, if we put $\rho_1 = \rho_{10}/\sqrt{\tau}$ it follows at once that

$$L^{(v)}(r_1) = \tau^{1/2}\mathcal{L}^{(v)}(r_{10}), \quad \text{where} \quad r_1 = r_{10}/\sqrt{\tau}.$$

Thus all that must be done to convert the tables from $\tau = 1$ to any other value

for τ, is to divide the r_1 column by $\sqrt{\tau}$ and at the same time multiply the $\mathcal{L}^{(k)}$ column by the appropriate power of the chosen τ: $-\frac{1}{2}$ in the case of the zero derivative, 0 in the case of first derivatives, $\frac{1}{2}$ for second derivatives, and 1 for third derivatives.

5. THE CONSTRUCTION AND USE OF TEMPLATES

The integrals (12), (14), (15) are most conveniently evaluated by breaking up the domain into compartments in each of which g may be given some mean value. If the compartment includes several stations, the mean value of g may be estimated from the data; otherwise, it is convenient to use the estimated value of g at the "mean value point" of the compartment. Intervals of r and θ should be chosen such that $\int\Lambda(\rho)d\rho$ and $\int\chi(\phi)d\phi$ take simple fractional values which are the same in each sector; then the processes of integration are replaced with those of summation, as, for example

$$U_x^0 = \sum_{s=0}^{\infty}\sum_{t=0}^{2\pi} g(r_{s+1/2}, \theta_{t+1/2})(\sin\theta_{t+1} - \sin\theta_t)\int_{r_s}^{r_{s+1}} \Lambda^{(ii)}(\rho_1)d\rho_1$$

where $g(r_{s+1/2}, \theta_{t+1/2})$ denotes the value of g at the "mean value point" of the sector included by r_s, r_{s+1}, and by θ_t, θ_{t+1}. The coördinates of this point are defined to be such that

$$\int_{r_s}^{r_{s+1/2}} \Lambda(\rho)d\rho = \frac{1}{2}\int_{r_s}^{r_{s+1}} \Lambda(\rho)d\rho \quad \text{and} \quad \int_{\theta_t}^{\theta_{t+1/2}} \chi(\phi)d\phi = \frac{1}{2}\int_{\theta_t}^{\theta_{t+1}} \chi(\phi)d\phi.$$

Suitable limits of r and θ for the construction of templates, which have been obtained by the graphical inverse interpolation of Tables I and II, are given for $\tau = 1$ in Table III. Conversion of these entries to values of τ other than 1 may be carried out in the manner already described. "Mean value points" may be found by subtabulation.

The function $\Lambda^{(i)}(\rho)$, however, requires special attention. In non-dimensional form, it is

$$\begin{aligned}\Lambda^{(i)}(\rho) &= s\pi^{1/2}\beta^{-1/2}e^{-\tau\rho_1^2}{}_1F_1(\tfrac{1}{2}; 1; \beta\rho_1^2)\rho_1 \\ &= s\pi^{1/2}\beta^{-1/2}e^{-\tau\rho_1^2/2}I_0(\tfrac{1}{2}\tau\rho_1^2)\rho_1.\end{aligned}$$

This function is shown graphically in Figure 2, for $\tau = 1'$. It is so slowly convergent as to be virtually stationary, and so it would be practically impossible to compute U^0 from a template drawn in the same manner as the others. On the other hand

$$i_x + i_y = 4U^0$$

for all of the groups, and since in non-dimensional units

$$i_x = s\pi^{-1/2}\tau^{1/2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} g(u_1, v_1)e^{-\tau v_1^2}du_1dv_1,$$

$$i_y = s\pi^{-1/2}\tau^{1/2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} g(u_1, v_1)e^{-\tau u_1^2}du_1dv_1,$$

it is easy to compute U^0 in this way. The values of

$$L^{(i)}(x_1) = \pi^{-1/2}\tau^{1/2}\int_0^{x_1} e^{-\tau u1^2}du_1$$

which are listed in Table III for $\tau = 1$ are quoted directly from the Tables of Probability Functions (New York, 1941), and a template drawn from these

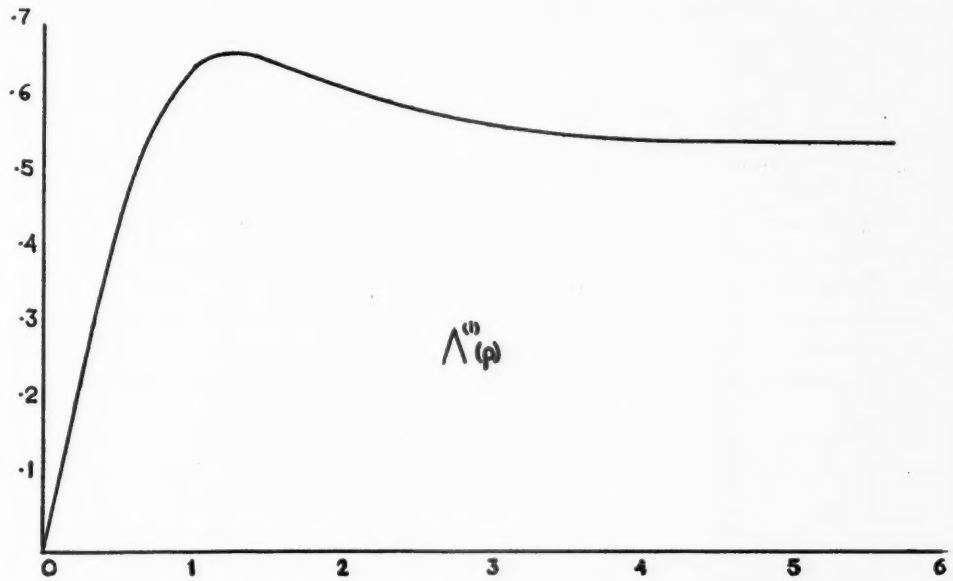

FIG. 2

values is shown in Figure 3. Beyond the boundaries of this chart, $x_1 = +x$, the body is assumed to behave as a point mass, and so there will be an additive correction term

$$2GM\left[1/z_0 - 1/(x^2 + z_0^2)^{1/2}\right],$$

which

$$\simeq \pi^{-1}\,\mathrm{I}_0^{\infty}\left[1/z_0 - (x^2 + z_0^2)^{-1/2}\right].$$

according to Gauss' Theorem. Methods for computing I_0^{∞} and estimating have been described in §8, Part I.

TABLE III

$L^{(ii)}(r_1)$	r_1	$L^{(iii)}(r_1)$	r_1	$L^{(iv)}(r_1)$	r_1
0.000	0.000	0.000	0.000	0.000	0.000
.025	0.647	0.10	0.324	.025	0.533
.05	0.880	0.20	0.473	.05	0.676
.075	1.062	0.30	0.596	.075	0.800
.10	1.236	0.40	0.714	.10	0.910
.125	1.408	0.50	0.833	.125	1.016
.15	1.583	0.60	0.957	.15	1.127
.175	1.774	0.70	1.097	.175	1.244
.20	1.994	0.80	1.270	.20	1.371
.225	2.255	0.90	1.517	.225	1.521
.25	2.570	0.995	2.302	.25	1.729
.275	2.937	0.999	2.633	.255	1.784
.30	4.03			.26	1.852
.325	5.57			.265	1.926
.35	7.58			.27	2.023
.375	10.37			.275	2.153
.400	14.32			.282	

$L^{(v)}(r_1)$	r_1	$L^{(vi)}(r_1)$	r_1	$L^{(vii)}(r_1)$	r_1
0.000	0.000	0.000	0.000	0.000	0.000
.10	.242	.010	.870	.05	.472
.20	.348	.020	1.088	.10	.619
.30	.442	.030	1.264	.15	.733
.40	.526	.040	1.431	.20	.840
.50	.611	.050	1.598	.25	.947
.60	.696	.060	1.772	.30	1.055
.70	.788	.070	1.974	.35	1.184
.80	.898	.080	2.221	.40	1.360
.868	.982	.090	2.554	.418	1.455
.936	1.242	.100	3.08	.435	1.700
.868	1.550	.110	4.00	.418	2.030
.80	1.678	.120	5.85	.40	2.236
.70	1.890	.130	11.35	.375	2.538
.60	2.102	.142		.35	3.18
.50	2.368			.335	4.18
.40	2.760			.320	
.30	3.47				
.20	4.95				
.10	9.24				
0.00					

$L^{(x)}(r_1)$	r_1	$L^{(viii)}(r_1)$	r_1	$L^{(ix)}(r_1)$	r_1
0.000	0.000	0.000	0.000	0.000	0.000
.10	.231	.01	.637	.01	.909
.20	.333	.02	.782	.02	1.091
.30	.421	.03	.891	.03	1.226
.40	.510	.04	.982	.04	1.337
.50	.598	.05	1.062	.05	1.440
.60	.700	.06	1.141	.06	1.543
.07	.848	.07	1.220	.07	1.644
.736	1.000	.08	1.299	.08	1.743
.70	1.160	.09	1.378	.09	1.850
.60	1.335	.10	1.457	.10	1.960
.50	1.466	.11	1.549	.11	2.087
.40	1.596	.12	1.650	.12	2.230
.30	1.730	.13	1.765	.13	2.404
.20	1.894	.14	1.910	.14	2.633
.10	2.116	.15	2.143	.15	2.96
0.00		.16		.16	3.38
				.17	4.28
				.1842	4.28

TABLE III—*continued*

$L^{(i)}(x_1)$, $L^{(i)}(y_1)$	x_1, y_1	sin $k\theta$	$\theta^0(k=1)$	$\theta^0(k=2)$	$\theta^0(k=3)$
0.000	0.000	0.00	0.00	0.00	0.00
.05	.089	.10	5.75	2.87	1.92
.10	.179	.20	11.53	5.76	3.84
.15	.272	.30	17.45	8.72	5.82
.20	.371	.40	23.58	11.79	7.86
.25	.477	.50	30.00	15.00	10.00
.30	.595	.60	36.87	18.43	12.29
.35	.733	.70	44.43	22.21	14.81
.40	.906	.80	53.13	26.56	17.71
.45	1.163	.90	64.15	32.08	21.38
.50		1.00	90.00	45.00	30.00
		.90	115.85	57.97	38.62
		etc.	etc.	etc.	etc.

6. CHOOSING THE PROPER AMOUNT OF SMOOTHING

Clearly templates constructed for $\tau = 1$ will not give the same accuracy to every problem; for the smaller the extent of the anomaly and the sharper its relief, the more it will be affected by the smoothing. Thus a "large" value for τ must be prescribed for an anomaly which is small and sharp in terms of s, or the anomaly itself will in effect become flattened by the smoothing and will tend to lose its character. As anomalies become extended, so it becomes possible to achieve the same accuracy using smaller values of τ. In every case, it is desirable to use the smallest value of τ_1—which implies the heaviest smoothing,—

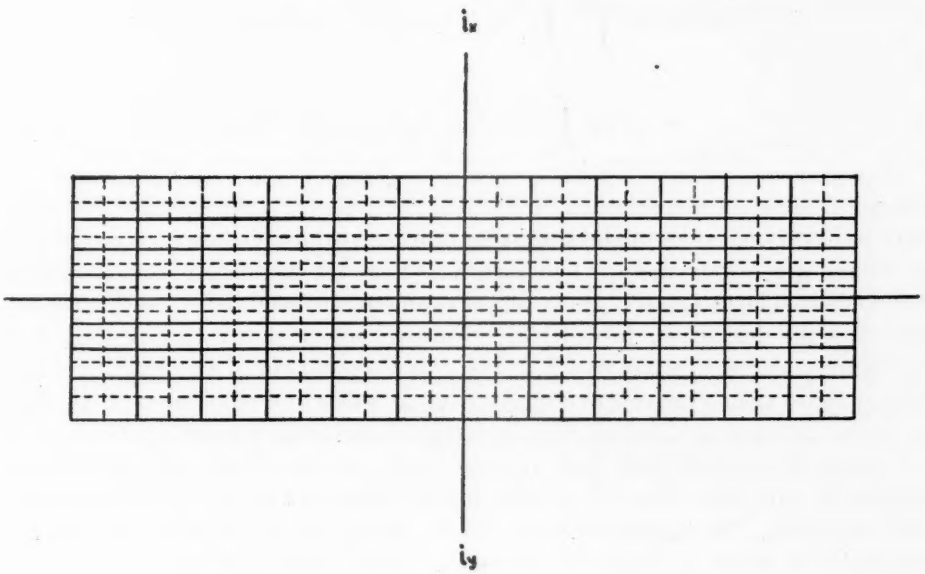

FIG. 3

that is consistent with the standard of accuracy to be imposed upon the problem, because the graphical computations are then most easy to perform and are least sensitive to errors in judgment.

The quantitative exposition of these statements must begin by defining a limit that distinguishes useful anomalies from uninteresting shallow effects. The definition offered is: if the centre of gravity of the geological body is estimated to lie at a depth below the surface of the ground less than the spacing unit s, then quantitative detailed interpretation must be regarded as futile and unwarranted. The virtue of this definition is evident from the consideration that whether the anomaly is small or the station spacing large, in either event there is too little working information recorded within the critical region.

A sufficiently comprehensive analysis of the problem may be obtained from consideration of the gravitational field of a point mass. The efficiency that will be demanded of the method is that the computed derivatives of the already-smooth field must agree with the theoretical values to within 5 percent. All derivatives of the same order can be computed with about the same precision, and so an examination of U_z^0, U_{zz}^0, U_{zzz}^0 will give a fairly complete picture of the degree of accuracy that may be realized.

The gravitational field over the horizontal plane $z=0$ due to a point mass located at a depth z below the origin of coordinates is

$$g(\rho) = kz/(\rho^2 + z^2)^{3/2},$$

and so

$$U_z^0 = kz \int_0^\infty \int_0^{2\pi} \Lambda^{(iii)}(\rho)(\rho^2 + z^2)^{-3/2} d\phi d\rho,$$

$$= 2\pi k z_1 \int_0^\infty \lambda^{(iii)}(\rho_{10})(\rho_{10}^2 + z_1^2)^{-3/2} d\rho_{10}. \qquad (17)$$

Similar expressions are obtained for U_{zz}^0, U_{zzz}^0. The integrands may be tabulated with ρ_{10} from the tables of the weighting functions, and are shown for a number of values of τ in the case $z_1=1$ in Figure 4. The "sharpening" effect of a large τ is obvious. The integrals of these curves expressed as fractions of the theoretical values of the derivatives to which they correspond are shown as functions of τ in Figure 5: curve 1 relates to U_z^0, curve 2 to U_{zz}^0, and curve 3 to U_{zzz}^0. It must be concluded that if the centre of gravity lies at a depth of only one unit, a value of about 35 must be assigned to τ in order to obtain 95 percent agreement.

These calculations have been repeated over suitable ranges of τ for each z_1 ranging in unit steps from 1 to 5. The curves corresponding to these calculations are not shown. The relation between τ and z_1 for 95 percent accuracy is approximately that shown in Figure 6; above the curve, differences are <5 percent;

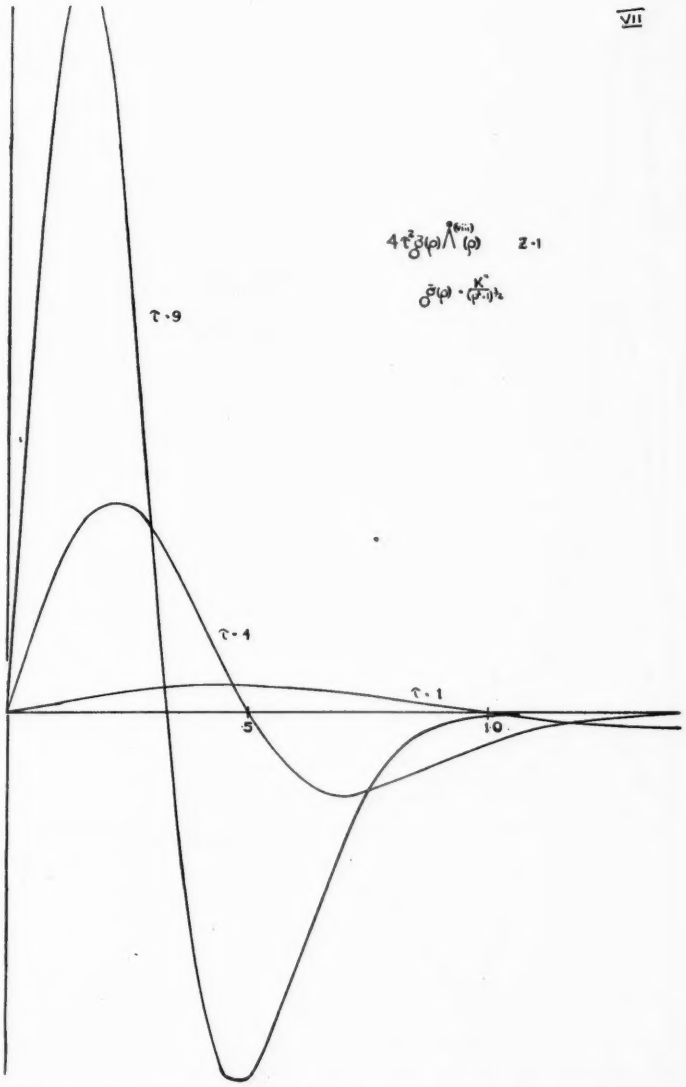

FIG. 4. Integrands of U_z^0, U_{zz}^0, U_{zzz}^0 of the gravitational field of a point mass buried at a depth of one unit.

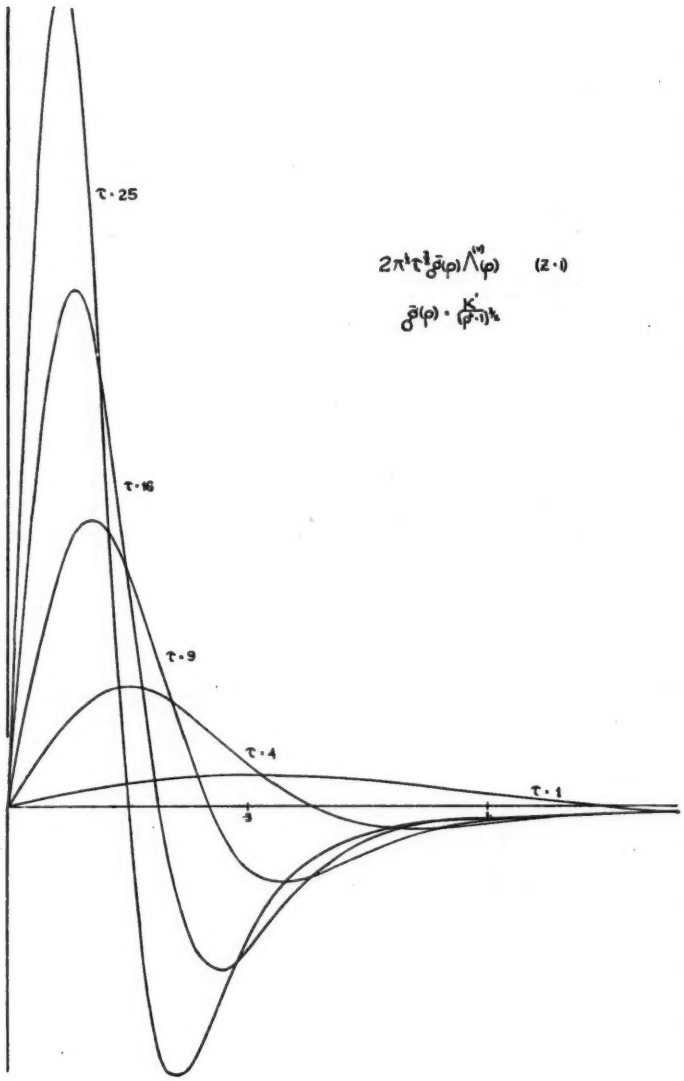

FIG. 4—*continued*

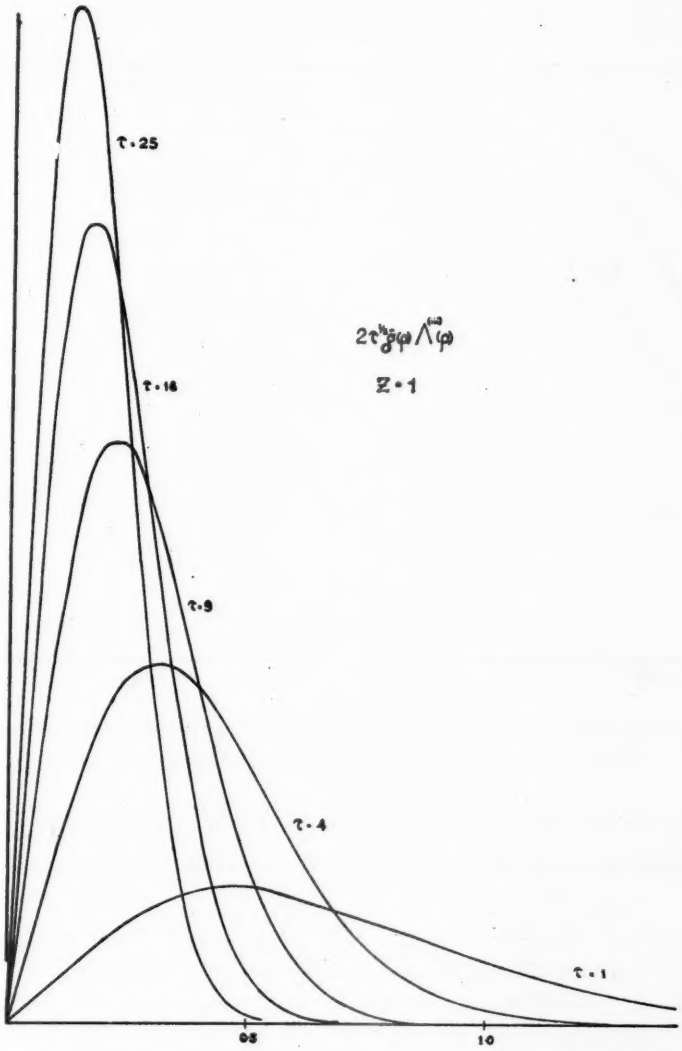

FIG. 4—*continued*

below, they are >5 percent. Actually, the curve varies somewhat with the different orders, but the differences are so slight that for sake of simplicity only a single relationship is shown, and it is approximately $Z_1^2\tau = 50$.

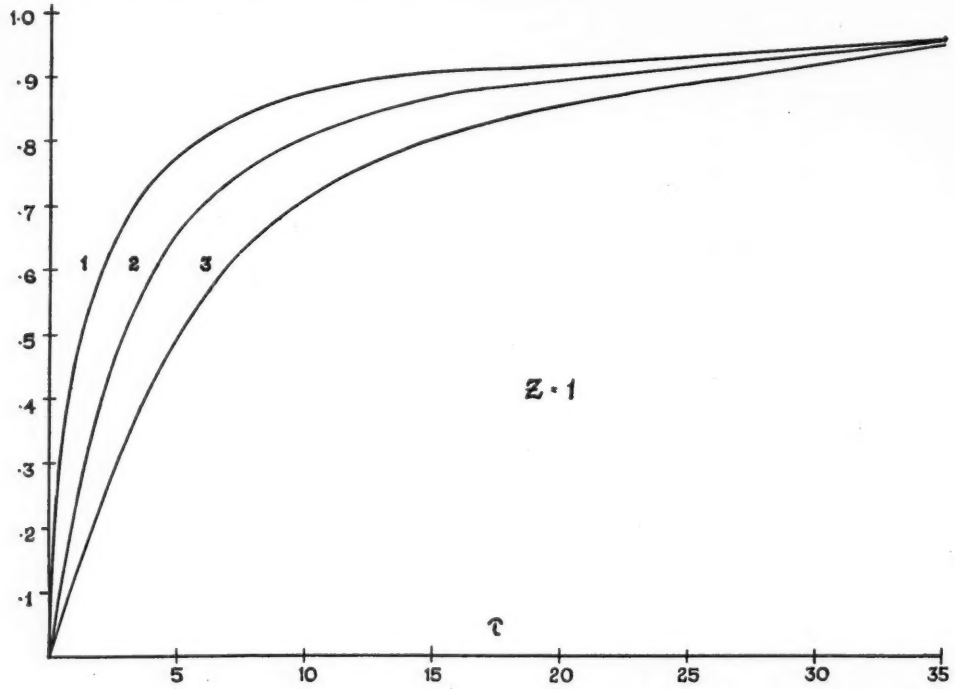

FIG. 5. Integrals of the curves of Figure 4 expressed as fractions of the theoretical values of U_z^0, U_{zz}^0, U_{zzz}^0 for a point mass at a depth of one unit.

To establish a practical system, the following rule may be set up:

If it is found that	Then give τ the value
$1.25 < z_0 < 1.5$	27
$1.5 < z_0 < 2$	16
$2 < z_0 < 3$	9
$3 < z_0 < 4$	4
$4 < z_0 < 5$	2
$5 < z_0$	1

7. THE PRACTICAL NECESSITY FOR SMOOTHING

Readers sometimes have asked if the introduction of analytical smoothing function is really essential to the method, and would not about the same result be achieved without its use. The reply is that in general no result at all can be achieved without it; and in the event that some readers may find this a question of some importance, the balance of this section is devoted to an appraisal of the

smoothing method as a device for computing the derivatives of a given potential field.

To begin with, it may be said that geophysical data are generally too irregular and uncertain to permit the use of finite-difference formulae; and that the use of integration charts for evaluating quantities such as derivatives is widely agreed to in principle, since random disturbances in the field tend to cancel one another

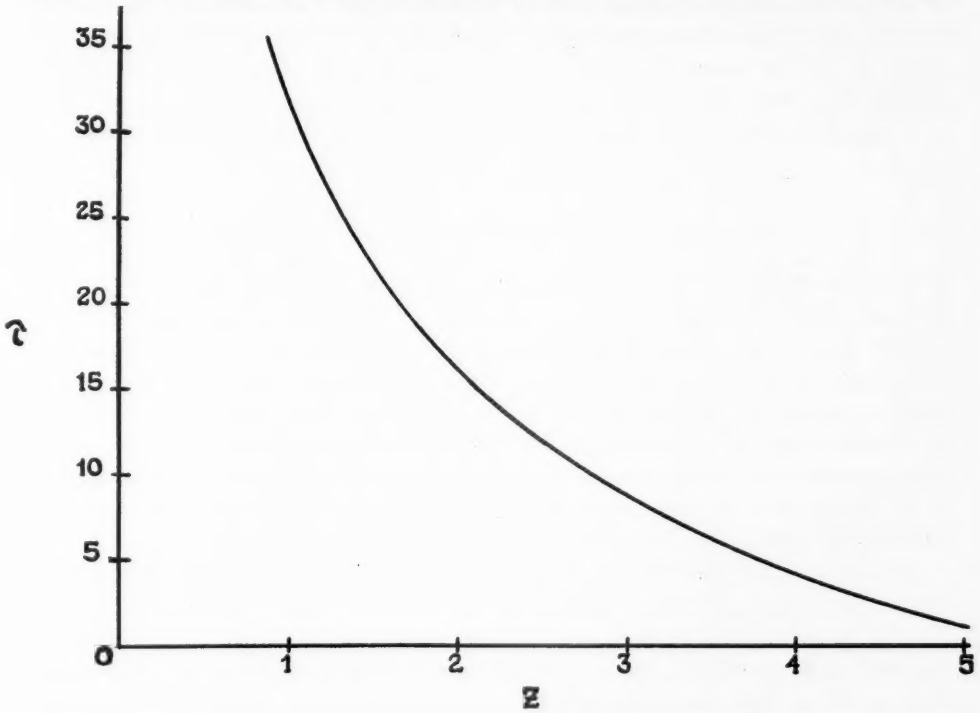

FIG. 6. The relationship between the depth z and the smoothing parameter τ for 95 percent agreement between the calculated and the theoretical values of the derivatives of the gravitational field of a point mass.

out in the computations. Evjen (1936) has suggested how a template may be constructed for the purpose of evaluating the vertical derivative of a given gravitational field (U_{zz}) at a point; and Kosbahn, using the same principle, has pointed out more recently that all derivatives may be computed from charts drawn from expressions such as (11) and (13); but the inefficacy of these charts must be apparent to anyone who has had occasion to use them. It is easy to see why. Take as an example, Evjen's expression for the second vertical derivative

$$U_{zz} = g_0/R - \int_R^\infty g(r)dr/r^2, \tag{18}$$

$$g(r) = 1/2\pi \int_0^{2\pi} g(r, \theta)d\theta$$

in which R is the largest radius within which g may be supposed to have a constant value g_0. U_{zz} in this expression is an explicit function of R, the choice of which lies very largely at the whim of the computer: as a result there is no way of knowing even approximately what magnitude of error has been committed by choosing a finite value for R, and so the answer loses a good deal of its meaning. Perhaps specific illustration will help. The most favourable case conceivable to which the expression (18) may be applied is the evaluation of the second vertical derivative of the gravitational potential of a point mass at a point directly above the mass; for here g does in fact remain quite constant within a small radius, and the integral part may be evaluated exactly without recourse to integration charts. The answer, expressed as a fraction of its true value, is:

$$f = U_{zz}{}^{0}{}_{(\text{calc.})}/U_{zz}{}^{0}{}_{(\text{theor.})}$$

$$= z/2R - \tfrac{1}{2}\left[\sqrt{R^2 + z^2}/R + R/\sqrt{R^2 + z^2} - 2\right].$$

This is the difference between two terms, both of which become large as R/Z becomes small. Actually plotting f against the non-dimensional quantity R/Z reveals that $f=0.9$ when $R/Z=0.135$. This means that in order to reproduce U_{zz} by (18) to within 10 percent of its theoretical value, R must be chosen of so small a size as to make both terms well over five times their difference. The conclusion must follow that in practical computations performed by integration charts, (where the residual data contain spurious disturbances) one cannot hope to do better than to arrive at a result having the proper order of magnitude, and that in many cases even the algebraic sign will be uncertain.

Added to this is the criticism that because of the highly singular point at the origin, the innermost circles of the chart are so small and cramped that estimations of sectorial mean values are difficult and haphazard, and the precision of the method of §8, Part I, for locating the centre of gravity is severely overtaxed. This point is best demonstrated by actual illustration, and for this purpose three diagrams drawn according to the suggestion of Kosbahn are displayed in Figure 7 opposite their counterparts constructed to the same scale with the aid of smoothing. It is left to the reader to decide which of the two schemes has the greater practicability.

Finally, it ought to be emphasized that Kosbahn's scheme provides for the direct computation only of even derivatives of z, such as U_z, U_{zz}, U_{zz}, etc. Odd derivatives such as U_{zz}, etc., may be found through equation (4) if the distribution of the potential U is known everywhere on the datum plane. Thus in order to compute odd derivatives (which are necessary to the methods of Part I), it is first of all necessary as an intermediate step to determine the distribution of the residual potential from the distribution of the residual gravity by applying the equation

$$U = \int_0^{\infty} \int_0^{2\pi} U_z(r_1\, \theta) d\theta dr$$

(which obtains from (3)) at each survey point. Clearly the amount of work involved in this procedure is altogether prohibitive, and if the boundaries of the anomaly are obscured by neighbouring influences, the results obtained will be worth little of the effort.

The smoothing method offers a remedy for each of these criticisms. The radial weighting functions $\Lambda(r)$ are, as Figure 1 shows, well behaved everywhere and reduce to zero at $r=0$; thus no arbitrary regions are excluded from the integration charts. The functions $L(r)$ are all slowly-rising for small r, and so

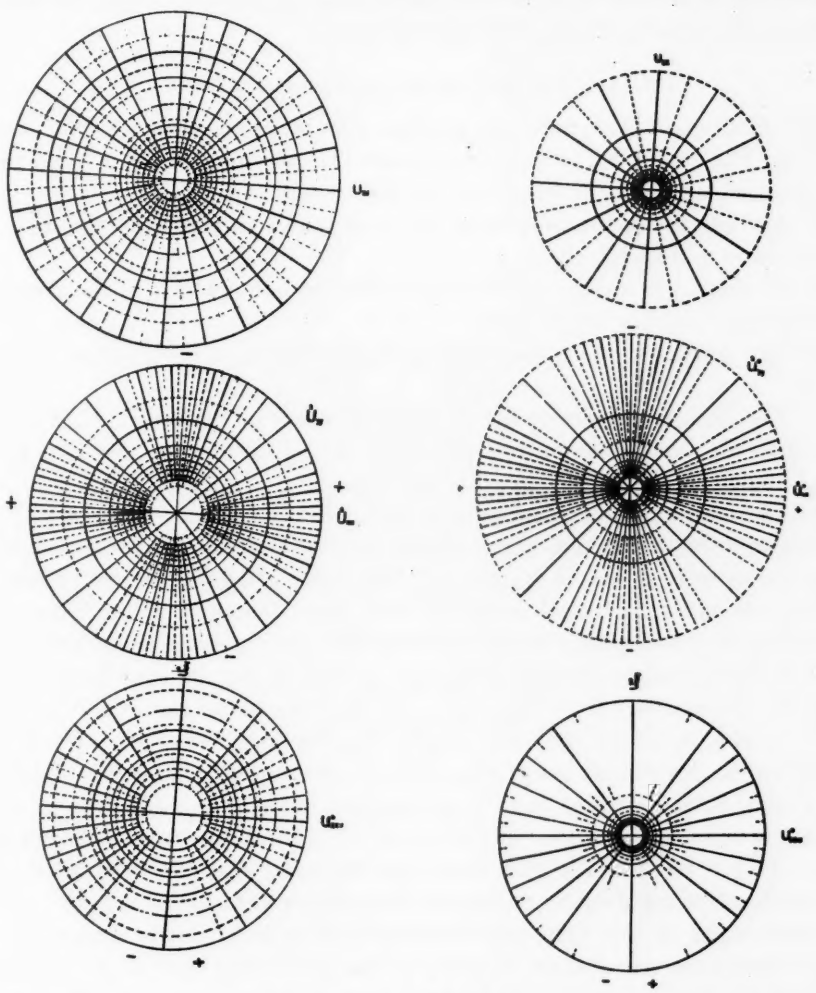

FIG. 7. Templates for evaluating U_{zz}^0, U_{zz}^0 and U_{zzz}^0. Those on the right hand side are constructed directly from expressions such as (11) and (13); those on the left from the values given in Table III. All of these charts were drawn for the same problem, and are shown on a true relative scale.

give rise to well-spaced annuli. And all derivatives may be computed directly from the data. The final testimony to the effectiveness of the smoothing method is the fact that the charts drawn from Table III give values for the derivatives of the artificial field to be described in the next section that lie within seven percent of the theoretical values, while about triple this discrepancy was obtained with charts drawn without the aid of smoothing. Arguments such as these, however, are concerned purely with utility. It should not be forgotten or overlooked that the smoothing method quite automatically sorts out contributions to the data from local shallow disturbances, and so it ought intrinsically to give results of greater practical significance.

8. APPLICATION TO AN ARTIFICIAL EXAMPLE

The methods of the previous sections will be applied now to an artificial problem. The praxis which has been chosen for this purpose is a uniform rectangular block having the following specifications:

1) The lengths of its three sides are 20, 40, and 50 metres in the directions of x', y', and z' respectively.

2) Its density relative to the surrounding medium (which is assumed to be uniform) is $+1$ gram cm^{-3}.

3) The depths of its centre below the horizontal datum plane are exactly 40 metres.

4) The Eulerian angles of the axes of symmetry of the block (x', y', z') with respect to the observer's frame of reference (x, y, z) are: $\Phi = 30$, $\Theta = 45$, $\Psi = 30$. These angles are defined in the usual sense (see e.g., Synge and Griffith).

An illustration appears in Figure 2, Part I.

The map of the normal gravitational field of this body over the horizontal plane $z = 40$ m is shown in Figure 8. These calculations have been made from the expression (I, 10), and contours have been sketched in by interpolating linearly between stations. Three observations are particularly striking: a) the general appearance of the contours gives no hint of the shape of the underlying body; b) at a distance from the z axis only slightly greater than the depth to the centre of the body, the contours become circular to within a very few percent, indicating that virtually all of the effect of asymmetry (moments higher than order zero) is lost, bearing out the assumption made to this effect in §8, Part I; c) even in the neighbourhood of the summit, the total quadrupole effect is of the order of 15 percent of the first term, and the combined effects of all moments higher than the quadrupole amount to less than 1 percent.

Derivatives of this field have been computed from charts drawn for $\tau = 4$, which were superimposed on the map at the point $A(O, O, z_0)$. It is interesting to compare the values obtained with those calculated theoretically from the given specifications. Cgs units are used throughout.

	U_x^0 $\times 10^{-4}$	U_y^0 $\times 10^{-4}$	U_z^0 $\times 10^{-4}$	U_{xz}^0 $\times 10^{-8}$	U_{zy}^0 $\times 10^{-8}$	U_{zz}^0 $\times 10^{-8}$
Computed by charts:	+1.57	+1.29	−1.62	−1.52	−1.16	+8.73
Calculated theoretically:	1.646	1.317	−1.746	−1.646	−1.315	9.125

	U_{zz}^0 $\times 10^{-8}$	U_{yy}^0 $\times 10^{-8}$	U_{zzz}^0 $\times 10^{-11}$	U_{zzy}^0 $\times 10^{-11}$	U_{zxx}^0 $\times 10^{-11}$	U_{zyy}^0 $\times 10^{-11}$	U_{xxx}^0 $\times 10^{-11}$
By charts:	−4.08	−4.58	1.81	1.61	3.49	3.94	−6.08
Theoretical:	−4.396	−4.729	2.057	1.643	3.407	3.823	−7.230

There are only two instances in which the error has exceeded seven percent; among the rest, the mean error is somewhat less than five percent, although

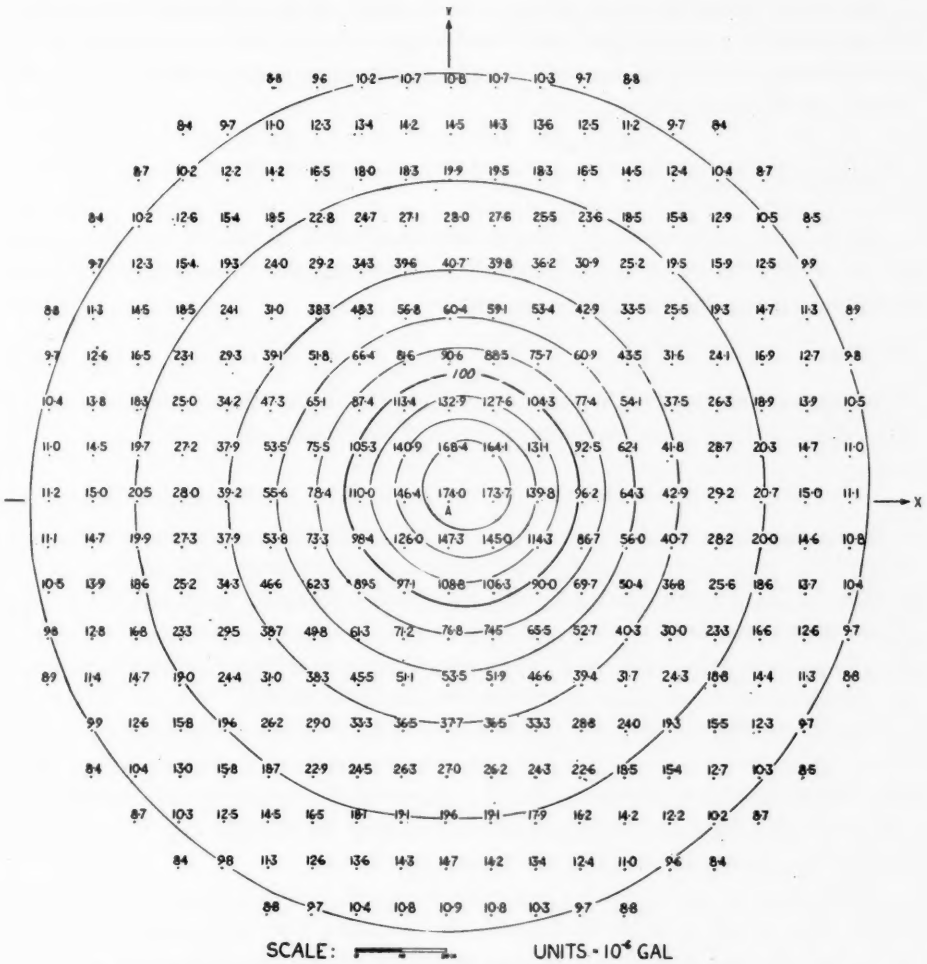

FIG. 8. Contours of the gravitational field of the rectangular block described in §9, over the plane $z=40$ metres.

consistently on the low side as one would expect. Nevertheless, the question arises: how sensitive are the inversion formulae of §7, Part I, to these unavoidable computational errors? To answer this question, some of the derivatives are recomputed with respect to a set of spatial axes that are more suited to the application of the formulae (II, 13); viz., a frame whose origin lies at A and whose x-

axis is inclined at 30 to the direction indicated in Figure 8. (In this frame $\Phi=0$). Again a comparison with calculated values shows the same sort of agreement:

	U_{xz}^0 $\times 10^{-8}$	U_{yz}^0 $\times 10^{-8}$	U_{xx}^0 $\times 10^{-8}$	U_{yy}^0 $\times 10^{-8}$	i_y
Computed by charts:	−2.06	−0.380	−4.34	−4.47	1.331
Calculated theoretically:	−2.080	−0.319	−4.364	−4.755	1.334

The weighted mean of the values of z_0 determined by these and the previous computations is 4.18×10^3 cms. The following is a comparison of the values of the reduced moments obtained from (I, 13) with those calculated directly from the dimensions of the block:

	B_0^0	B_2^0	B_2^2
From computed derivatives:	2.46×10^3 gm	2.04×10^9 gm cm^2	$-.965\times 10^9$
Calculated theoretically:	2.664	1.668	−.999

Actual dimensions may be determined from these values by expressing two of the parameters in terms of the third and solving the cubic equation by the Newton-Raphson method. The result is:

$$\Theta = 41^0, \qquad \Psi = 31.5^0, \qquad 2a = 17.4\text{ m}, \qquad 2b = 39.4\text{ m}, \qquad 2c = 53.6\text{ m}$$

which seems to warrant the conclusion that mechanical errors in the computations *per se* distort the results to an inconsequential amount.

9. APPLICATION TO A GEOPHYSICAL SURVEY

For illustration of the practical application of these methods, the example chosen is a gravimetric survey conducted by the Dominion Observatory over sulphide concentrations at East Sullivan Val d'Or, Quebec, in June 1947 (Innes, 1949). The purpose of the survey was to provide an objective test of the performance of the gravimeter in delineating an orebody whose dimensions and density characteristics are quite accurately known from drilling.

The topographic relief does not exceed 20 feet on the East Sullivan properties, so that the ground surface itself may be chosen as the datum plane without error. The sulphide concentrations are covered with a swampy overburden varying in depth between 10 and 50 feet, and having an average depth of about 15 feet. Of the geology of the area, Dr. Innes says:

"The area is underlain by volcanic rocks of Keewatin age, which consist chiefly of a series of acidic to basic lavas, encasing the ore deposit, and which in its vicinity are highly altered and replaced by the disseminating sulphides. The ore consists chiefly of pyrite, chalcopyrite, pyrrhotite, and sphalerite, with a very minute amount of galena, and carries some gold and silver. It occurs in three main masses, known as the West, Central and East orebodies; there is some indication from drilling that the Central and East orebodies merge into one body at depth. A major structural feature associated with the deposit and bounding the orebody to the southeast and east is an intrusive mass of coarse syenite porphyry."

Numerous drill core samples of the rock formations in the vicinity of the sulphides, and the specific gravity measurements for ton lots of the sulphides provided by the management of the East Sullivan mines revealed the mean density contrast between the sulphides and their host rocks to be about 0.7 gm cm^{-3}; between the host rocks and the syenite prophyry, the contrast varied from 0.1 to 0.2 gm cm^{-3}.

Lines of equal Bouguer anomaly showed a strong directional trend approximately southwest to northeast over the region underlain by the syenite intrusive, and their spacing converged quite sharply toward the southeast. The total variation was from -2.14 milligals in the southeast corner of the area to $+0.60$ milligals over the West orebody. The major influences of this gradient were removed by assuming that the effect of the syenite intrusive is represented by the smoothest monotonically-rising profile that can be drawn in the direction of the maximum gradient. This correction curve was assumed to be unchanging in the direction at right angles to the profile, so that the artificial regional datum-level can be pictured as a smooth cylindrical surface whose axis runs approximately southwest to northeast. In actual fact, the real surface showed a pronounced warping to westward near its southern extremity.

A copy of the residual gravity map calculated by Innes is shown in Figure 9. The ore bodies at the surface and at the 450 foot level (as far as the drilling had developed) are outlined. In Figure 10 is shown a section of the west orebody in the vertical plane through E. 3,300.

The following is a summary of the step-by-step interpretation of the regionally-corrected gravity anomaly map in the vicinity of the west orebody.

A. Approximate depth to centre: the minimum half-width of the anomaly is approximately 270 feet; the half-width at right angles to this minimum is roughly 350 feet. The maximum anomaly is 8.0×10^{-4} cm sec^{-2}, and the largest plausible density contrast between the sulphide and its host rock is 1 gm cm^3 If these values are substituted into (I, 26), then it turns out that $z_0 \simeq 234$ feet, or 2.34 non-dimensional units.

Location of the Centre of Gravity: The charts drawn for the integrals I, J and K (Part I), superposed over the point marked A, yielded the following answers:

$I = 1844$, for $R = 267'$, $J = 128$, for $R = 247'$, $K = -315$, for $R = 247'$.

Substitution of these values into (I, 24, 25) gives

$$x = 17 \text{ feet}, \qquad y = -39 \text{ feet}.$$

This point is marked O on the map.

B. Measurement of the derivatives: Axes OX and OY following the principal directional trends of the contours are also shown on the map. Charts for computing the derivatives were drawn for $\tau = 16$ and superposed on these axes. The following are the values obtained (in cgs units):

$U_z = 7.00 \times 10^{-4}$ $U_x = 6.40 \times 10^{-5}$ $U_y = 9.96 \times 10^{-5}$

$U_{xx} = -7.85 \times 10^{-8}$ $U_{yy} = -9.00 \times 10^{-5}$ $U_{zz} = 16.72 \times 10^{-8}$

$U_{zx} = -1.98 \times 10^{-8}$ $U_{zy} = -4.60 \times 10^{-8}$ $U_{zzz} = -5.38 \times 10^{-11}$

$U_{zzx} = 0.344 \times 10^{-11}$ $U_{zzy} = 1.36 \times 10^{-11}$ $U_{zxx} = 2.52 \times 10^{-11}$

$U_{zyy} = 3.39 \times 10^{-11}$ $i_x = 13.3$ $i_y = 11.1$

C. Interpretation of the Results: Much of the anomaly has been obscured

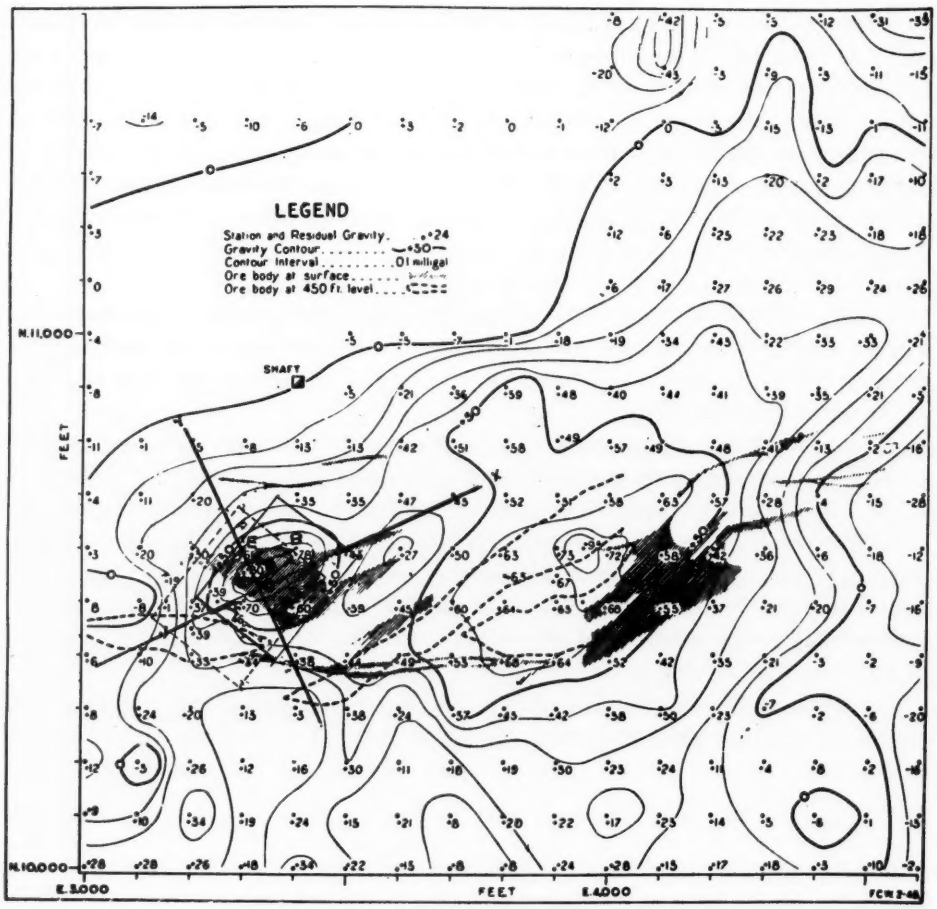

FIG. 9. Contours of residual gravity after regional correction has been applied.

by the neighbouring field of the East orebody and by residual regional effect to the south. These two influences have combined to give values near the boundary that are rather too high to the east and too low to the west, and so it would be inadvisable to place very strict reliance upont the correctness of the derivatives.

Moreover, there are so few station values within the critical area that the shape of the contours may be open to question. On this account it is advantageous to presume the highest symmetry that is consistent with the geology of the area, for this will provide the greatest number of cross-checks on the calculations. For this reason the orthorhombic class is suggested, and proceeding accordingly, it is found that:

Weighted $z_0 = 240$ feet.

$$\Theta = 4\tfrac{1}{2}^\circ, \qquad \Psi = 30^\circ.$$

$B_0^0 = 4.22 \times 10^4$, $B_2^0 = 3.36 \times 10^{12}$, $B_2^2 = -1.42 \times 10^{12}$ cgs units.

If the model chosen is a rectangular block, then it turns out that

$$a = 79 \text{ feet}, \qquad b = 188 \text{ feet}, \qquad c = 268 \text{ feet}.$$

D. Adjustment of the parameters: These values of a, b and c define a structure which is larger than expected,—very probably as a result of the uncertainty about the regional level of zero anomaly. A first relaxation is performed at the points B, C, and D giving $\Delta' a = 63$ feet, $\Delta' b = -44$ feet, $\Delta' c = -110$ feet. These deformations are quite violent, indicating that the first solution was rather a bad one. The subsequent course of the relaxation is given in summary as follows:

$\Delta'' a = +83$ feet, $\Delta'' b = -69$ feet, $\Delta'' c = -29$ feet (Points *D*, *E*, *F*)

$\Delta''' a = -89$ feet $\Delta''' b = +35$ feet, $\Delta''' c = +63$ feet

The reversal of sign after the third relaxation suggests that the process has probably just begun to converge. The calculations could be continued to a finer result, but little more would be demonstrated by doing so. If instead we accept half of the third deformations, we arrive at the following result: $a = 136$ feet, $b = 110$ feet, $c = 226$ feet. This structure is outlined in plan at the 0 and 450 foot levels in Figure 9, and in section through E. 3,300 in Figure 10. Evidently the residual gravity field does not truly reflect the action of the west orebody. The discrepancy in size between the actual and the theoretical bodies may indicate that the choice of the regional level of zero anomaly was in error, or possibly that the density of the sulphide increases toward the centre; the inconsistency in the general form can only be explained by the presence of part of the regional anomaly in the residual data, combined with a paucity of information within the critical area. This survey is an ideal example only in the respect that disturbing topographical effects are negligible and that the form of the actual body is quite well known.

10. DISCUSSION

The investigations described in §§8 and 9 suggest that three-dimensional interpretation of non-extended geological bodies by the method of multiple moments can be practicable and may frequently be useful. However it is only fair to warn that if the data are poor in quantity and in quality, the calculations

may become so tedious that the quality of the results obtained may not then adequately repay the considerable amount of arithmetical work involved. In such cases the inversion formulae can be simplified somewhat by introducing additional hypotheses that may relate to a particular geology (e.g. $\psi = 0$ and assumed value for Θ), but even this is not guaranteed to be effectual. The surest provision that can be made for the speedy convergence of the calculations and for the attainment of results of good practical value is an abundance of observations in the

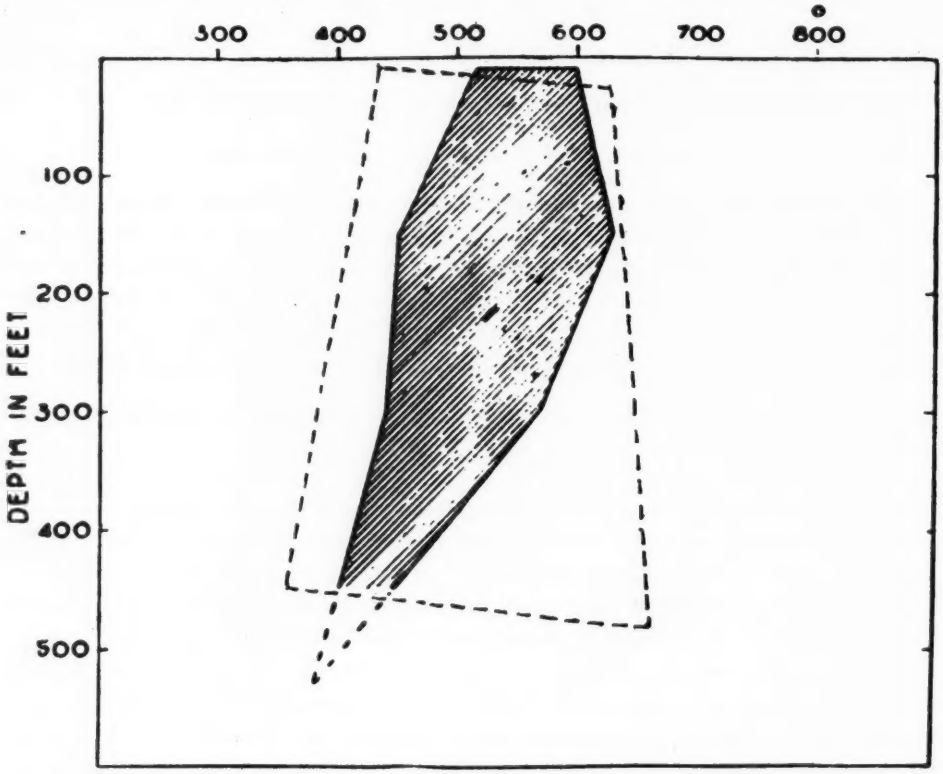

FIG. 10

neighbourhood of the anomaly peak. It does not seem likely that sufficient detail for the successful application of these methods will be found in the "reconnaissance" type of survey; it is suggested rather that they may find their greatest usefulness in providing a basis for systematic exploratory drilling for the purpose of proving reserves in an area that early reconnaissance work has shown to be interesting and which subsequently has been surveyed in finer detail.

When a regional correction has been applied to the data by intuitive or haphazard procedures, as is the custom (§9 is an example), some of the regional effect usually remains in the residues, although one cannot know how much. What

is worse is the fact that it is distributed systematically,—not randomly, through the field, so that it deforms the contours more or less seriously from the pattern that is characteristic of the geological bodies present. Under such circumstances, the value of the ability of three-dimensional methods to determine structures capable of reproducing the residual field may be questioned. The only answer to the problem of course, lies in improved and more methodical procedures for applying the regional correction. It may be suggested that the same smoothing function which is able to sort out random fluctuations from the main anomaly should be able to separate satisfactorily a local anomaly from a regional anomaly, without having to inquire into the cause of either phenomenon. However, this is probably best regarded as a separate problem from interpretation, and so no more will be said on the matter beyond pointing out that such a process if successful would remove one of the main obstacles to the use of direct interpretation procedures.

The author, in conclusion, wishes to acknowledge his thanks to Mr. Clyde Lonergan of the Computation Centre of the University of Toronto for performing the computations which appear in Table I; and to Dr. G. D. Garland of the Geophysics Laboratory for reading the manuscript and offering some helpful suggestions during its preparation.

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PROCEDURES FOR THE DIRECT EMPLOYMENT OF NEUTRON LOG DATA IN ELECTRIC LOG INTERPRETATION*

M. R. J. WYLLIE†

ABSTRACT

It is well-known that under suitable borehole conditions there is a relationship between porosity and the deflection of a neutron log curve. This relationship finds practical use, calibration of the neutron deflections being made by reference to porosities measured on cores. It is shown that theoretically core analysis is not mandatory for neutron log calibration and that the calibration may be achieved by direct plotting of suitable neutron and electric log data. For this purpose the concept of the neutron deflection corresponding to a formation factor of unity is introduced. It is shown that this concept makes it possible to use a combination of electrical and radioactivity log data to locate zones of oil saturation in carbonate rock formations and even to estimate the oil saturation. Application of the method to sandstones is also considered. In oil-base mud logging, neutron-log data may be conveniently combined with resistivities read off induction logs to give information bearing on the location of saturated zones and the estimation of connate water salinities. Finally a combination of electrical and radioactivity log data is theoretically capable of contributing to the quantitative elucidation of the "dirty sand" problem.

INTRODUCTION

As a consequence of the new and improved logging services that have been offered to the oil industry, the past decade has seen tremendous impetus given to the art of well log interpretation. Three papers, which are adequately documented and which conveniently summarize the most outstanding of these developments, were presented at the recent World Petroleum Congress (1, 2, 3).

It is a noteworthy feature of these papers that no attention is given by their writers to interpretation procedures that involve the simultaneous use of both electric and radioactivity well logs.‡ This omission probably has its origin in two considerations: the youthfulness of the log interpretation art and the fact that until recently no single company has offered a full selection of both electric and radioactivity logging services.

It is the intention of this paper to show that in theory at least the combination of neutron-log data with suitable electric log data may greatly increase the practical utility of both logs. Like any other system of log interpretation, the method discussed will not be found indiscriminately applicable. However, it appears that it may be expected to be most useful when applied to logs run through limestone and dolomite sections or to logs run in oil-base mud. Since longs run under these conditions are often difficult to interpret, the method may be found to be of im-

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‡ Russell (13), however, has recently suggested that neutron logs may contribute to the interpretation of electric logs

mediate practical utility. In addition, however, it is hoped that the paper will suggest directions in which improvements in logging instruments might profitably be sought, as well as showing the value of extending the practice of making simultaneous radioactivity and electric log surveys. Simultaneous neutron and focusing-type resistivity log surveys appear, for example, to represent a combination often preferable to the present combined gamma-ray log and resistivity-log survey.

GENERAL CONSIDERATIONS

The introduction of resistivity logs of the focusing type such as the Induction log and Laterolog (2) and Guard Electrode (4) have materially eased the problem of determining the true resistivity of formations. It is true that none of these logs are entirely unaffected by the nature of the borehole fluid, the extent of filtrate invasion into a formation, the thickness of a formation or the properties of adjacent formations. Nevertheless, by comparison with earlier electric logs the new devices may be said to be relatively unaffected by these variables and to give in many important instances an excellent direct approximation to the true resistivity of a formation and even, in a thick non-homogeneous formation, the distribution of resistivity. At present efforts are being directed to the problem of supplying charts which will serve to correct to true resistivities the apparent resistivities given by these focusing logs. If these efforts are successful the value of these logs will be enhanced. Even without correction charts and particularly if the resistivity of the drilling mud used is adjusted to a value best suited to the log being run (high resistivity for Induction logs, low resistivity for other types), the apparent resistivity is often from 80–120 percent of the true value.

Log interpretation is fundamentally a three-fold problem. It is necessary to determine true formation resistivity, interstitial water resistivity and formation factor (1). If the first parameter is determinable from a resistivity log and the second by calculation from the S.P. ccrve, only the third remains to be found. It is this third parameter, formation factor, that may be estimated from neutron log data.

The formation factor, defined as the resistivity of a fully brine-saturated rock divided by the resistivity of the saturating brine, is a function of the porosity of the rock and the manner in which the pores are interconnected. Considerable attention has been paid to the form of the expression relating formation factor to porosity. It was originally suggested by Archie (5) that in any particular formation the formation factor, F, appeared to be related to the fractional porosity, ϕ, by an expression of the form:

$$F = \phi^{-m}. \tag{1}$$

The exponent, m, often designated cementation factor, was shown by Archie to be rather constant. The fact that in any particular formation a plot of formation factor against porosity generally gives a grouping of points encompassing a rather small porosity range makes it difficult to decide on the exact form of the

relationship between the two parameters. However, there is some theoretical basis for the belief that in consolidated sandstones, at least, the relationship is of the form:

$$F = \text{Constant } \phi^{-k} \tag{2}$$

where both the constant and the exponent, k, reflect the properties of the original unconsolidated sand body from which a sandstone was derived. Winsauer, Shearin, Masson, and Williams (6), on the basis of somewhat limited data, have suggested a value of 0.62 for the constant and 2.15 for the exponent, k. These values are essentially averages but are in reasonable conformity with more extensive formation factor and porosity data plotted by Archie (7). Archie actually drew averaging lines through his data and these lines follow Equation (2) rather than Equation (1), but he does not explicitly note the consequences of his construction.

For clean sandstones experience has taught that the value of the exponent m lies within the range 1.4 to 1.9 in the great majority of cases. If something is known of the general texture of rocks in a particular area the limits of m may be narrowed. This is particularly true if very friable rocks need not be considered, for then the minimum value of m may be only 1.5 to 1.6. The form of Equation (1) is such that for any porosity any uncertainty in m leads to considerable uncertainty in the value of F. Although this fact will be shown to be of somewhat lesser importance in log interpretation than might at first be thought, it is desirable to use a more accurate general relationship between F and ϕ if one exists. It seems probable that an equation of the from of Equation (2) will satisfy this requirement and thus materially reduce the possible spread in the value of F if ϕ is known, or vice versa. Expressions of the form of both Equations (1) and (2) are considered below.

In clean carbonate rocks, the value of the exponent m in Equation (1) is generally higher than in sandstones; it seems to vary from about 1.8 to 2.3 with an average of about 2.0. Whether an expression having the form of Equation (2) will be found applicable to carbonate rocks is not yet known.

The use of neutron logs for the determination of porosity has been discussed and summarized by Fearon and Mardock (3). In essence the method depends upon the fact that over the comparatively small porosity range encompassed by natural rocks, there is a semi-logarithmic relationship between the hydrogen content of rocks and the deflection of the neutron curve. If all the hydrogen is in liquid-filled pores in the rock (i.e., a rock free from hydrogenous minerals) the neutron deflection is a function of the porosity of the rock. Actually the hydrogen content of the liquid filling the pores is a factor of importance. The response of the neutron curve to similar water-bearing or oil-bearing rocks is sensibly the same, but this is not the case if dry gas occupies the pores of the rock, since the density of the hydrogen packing in gas is markedly less than the hydrogen density in oil or water. However, since the radius of investigation of the neutron de-

vice from the borehole into a formation is comparatively small, the neutron log often reflects only the hydrogen content of formation invaded by mud filtrate. This is particularly so in low porosity formations, although it is true that in low porosity formations the radius of investigation of a neutron log is a maximum. Since dry gas may be almost completely displaced by mud filtrate in the invaded zone, dry gas is a somewhat less significant factor in neutron log interpretation than might be expected or even desired. Indeed the many occasions on which it is impossible to locate gas/oil contacts on a neutron log is probably evidence of this fact.

It is apparent that if formation factor, an electric log parameter, may be expressed in terms of porosity, and porosity is in turn related to neutron-curve deflection, it should be possible to devise a joint electric log-neutron log interpretation procedure. A method of achieving this end is now given.

THE APPARENT FORMATION FACTOR-NEUTRON DEFLECTION PLOTTING METHOD

In its simplest form the method consists of the following: *Plot the apparent formation factor (true formation resistivity divided by connate water resistivity) as ordinate on a logarithmic scale and the corresponding neutron curve deflection in consistent units on a linear scale as abscissa. Then points corresponding to rocks containing oil will fall above points corresponding to rocks containing water, and the magnitude of the displacements will be related to the degree of oil saturation.*

The validity of this construction may be shown by reference to Figure 1. On this figure a typical semi-logarithmic response between neutron log deflection and porosity has been drawn (using, for example, porosities from core data). Note that this line has been extended to $\phi = 1.0$, far beyond the normal porosity limits over which the semilogarithmic relationship has been shown to hold. It must, therefore, be emphasized that this construction is purely a geometrical one; it does not imply that if any real porous medium could be obtained with a porosity covering the same wide range the measured porosity-neutron deflection relationship would be that shown. It is, indeed, almost certain that in practice there would not be an exponential relationship between the two parameters at very high porosities. Nevertheless, this construction is valid if its actual physical limitations are borne in mind. The neutron deflection corresponding to a porosity of unity is obtained. This deflection has been designated 10 on Figure 1. In general, the deflection corresponding to a porosity of unity will be smaller than any deflections actually recorded on the log. It must be emphasized that this deflection will not correspond to the so-called absolute zero reference line of a neutron log. If, however, an absolute zero reference line is marked on the log it is convenient to generalize the neutron data by plotting all deflections in so-called standard units from the absolute zero reference line as datum. Alternatively a calibration in microroentgens per hour may ultimately be found feasible.

While the neutron deflection corresponding to a porosity of unity is fictitious in the sense that there is no independent method for its evaluation, it is, nonethe-

less, of significant practical importance. It is the neutron deflection that would correspond theoretically to a formation factor of unity. It must also be emphasized that the neutron deflection corresponding to a formation factor of unity is a function of the type of formation being logged and of the diameter of the borehole. The characteristics of the logging instrument are also significant, although these characteristics seem to be standardized (at least within individual service

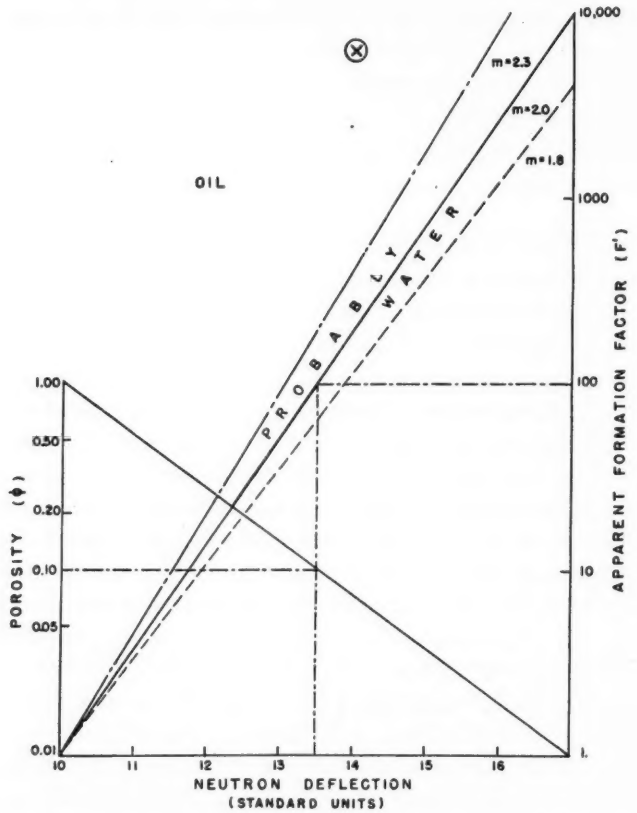

FIG. 1. Method of plotting apparent formation factors against neutron deflections to estimate oil saturation and to determine the porosity-neutron deflection calibration when $F=\phi^{-2.0}$.

companies). For a constant borehole size the deflection may not be identical in sandstones and carbonate rocks, since an identical value in the two cases would imply porosity-neutron deflection relationships that were independent of chemical differences between the two rock matrices. Perhaps the effect of variations in borehole size are most critical, since the consequences of such variations on a porosity-neutron calibration curve are well-known, but, as yet, are not subject to correction.

It is apparent from Figure 1 that the neutron deflection corresponding to a

porosity of 0.10 is 13.5. If Equation (1) is used with $m = 2.0$, the formation factor at this porosity is 100, and the corresponding neutron deflection still 13.5. Hence, a straight line may be drawn as shown from $F = 1$, neutron deflection = 10, through $F = 10$, neutron deflection = 13.5. Formation factors may be plotted as shown on the logarithmic scale of standard semi-logarithmic graph paper. On this paper the formation factor corresponding to $\phi = 0.10$ is a convenient second point to plot, but, of course, the choice of this porosity is arbitrary. Indeed it is evident that any two points on the porosity-neutron deflection curve could be chosen, thus obviating the original extrapolation to $\phi = 1.0$ and diminishing the size of the plot. Nevertheless, the construction shown in Figure 1 is generally convenient and more graphic than an abbreviated plot that involves the same basic assumptions. It is evident from simple geometrical considerations that on Figure 1 the logarithm of formation factor is actually being plotted against the logarithm of porosity, the porosity scale of the abscissa being a bastard logarithmic one defined by the angle the porosity-neutron deflection straight line makes with the porosity ordinate.

If, in carbonate rocks, it is assumed that m may vary from about 1.8 to 2.3, a similar construction may be used to draw neutron deflection-formation factor lines for exponents having these extreme values. This is also shown on Figure 1. Figure 1 reveals that if the apparent formation factors, F', of carbonate rocks of a particular composition (for uncased holes of the same diameter) are plotted against corresponding neutron deflections (in consistent units and from the same zero datum) the points corresponding to water-bearing formations will group together in a comparatively narrow segment. This segment will be bounded by lines corresponding to $m = 2.3$ and $m = 1.8$. In Figure 1 it is designated "probably water." If points fall in the region above the line of $m = 2.3$, either the rock section corresponding to the point has a cementation factor, m, that exceeds 2.3, or it contains oil. Since the probability of m exceeding 2.3 is small, the probability that the point corresponds to an oil-saturated zone is correspondingly great. If $m = 2.0$ is accepted as a valid average value for the cementation factor of carbonate rocks, the resistivity index, I, is the ratio of the apparent formation factor at any neturon deflection to the formation factor at the same deflection that lies on the line $m = 2.0$. Thus, in Figure 1, if X is a plotted point, corresponding to $F' = 6{,}000$, neutron deflection = 14.0, I for the point X is probably 6,000/200 or 30 and the fractional water saturation, S_w, from $I = S_w^{-2}$, about 18 percent.

In practice if the principles shown in Figure 1 are to be used, it is essential that at least some part of the section examined should be water bearing. Economically unsatisfactory as this condition may be, it is, nevertheless, one that rarely serves to prevent the method being employed. Accordingly, apparent formation factors are plotted against neutron deflections, preferably for sections of the formation for which both the resistivity and the neutron deflection are rather constant over a distance of several feet. Sections which a Microlog or other contact-type log have shown to possess permeability are to be preferred for obvious

reasons. The best straight line is then drawn through the scatter of points corresponding to the lowest apparent formation factors (at any neutron deflection) and this line is assumed to correspond to $m = 2.0$. The line is extrapolated to cut the abscissa at $F = 1.0$, thus giving the neutron deflection corresponding to a porosity of unity. Finally a line is drawn from the point $\phi = 1.0$ and appropriate neutron deflection, through $\phi = 0.10$ and the neutron deflection corresponding to the average value of $F' = 100$. This construction, which is the reverse of that described above, leads to the drawing of a porosity-neutron calibration curve without any core analysis data being required.

In Figure 1, the segment bounded by the lines $m = 1.8$ and $m = 2.3$, has been designated as "probably water." This equivocal designation stems from the fact that if a formation has a cementation factor of only 1.8 and contains some oil, its apparent formation factor will be increased. If this increase is not sufficiently great to give rise to an apparent formation factor which exceeds that of a water-bearing formation having the same porosity and a cementation factor of 2.3, the presence of some oil in the formation will not be recognized. Hence, the interpretation of points falling within the segment bounded by the lines $m = 1.8$ and $m = 2.3$ cannot be unequivocal. If the resistivity index exponent, n, in the relationship $I = S_w^{-n}$ is assumed to be 2.0, it is possible to define the limits of oil saturation between which the uncertainty arises. The uncertainty will be a function of the porosity of the formation and for carbonate rocks is calculable from the relationship:

$$I = \frac{F' \text{ for } m = 2.3 \text{ at any porosity}}{F' \text{ for } m = 1.8 \text{ at the same porosity}}. \tag{3}$$

Data for carbonate rocks are given in Table I. It is seen that in the worst case, that of a formation of 2 percent porosity, the water saturation must be less than 38 percent if interpretation is to be unequivocal. At a porosity of 10 percent, the water saturation need only be less than 57 percent. These figures are rendered more favorable if the resistivity index exponent is greater than 2.0 or if closer limits than $m = 1.8$ and 2.3 can be put upon the cementation factor, m, in Equation (1).

TABLE I

WATER SATURATIONS REQUIRED FOR UNEQUIVOCAL LOCATION OF OIL ZONES IN CARBONATE ROCKS

Porosity of Formation	F for $m = 2.3$	F for $m = 1.8$	Oil Not Detectable Unless Water Saturation Less Than:
			$n = 2.0$
0.20	40	19	69%
0.15	80	47	63%
0.10	199.5	64	57%
0.08	335	95	59%
0.06	650	170	51%
0.04	1,600	340	46%
0.02	7,700	1,150	38%

For sandstone formations, if m is considered to show possible variations from 1.4 to 1.9 with an average of about 1.7, a similar calculation to that made above for carbonate rocks leads to the data recorded in Table II. Since the porosity of sandstones is generally higher than that of carbonate rocks, the possibilities of unequivocal interpretation are reasonably favorable in spite of the considerable spread in the values of m assumed.

TABLE II

WATER SATURATIONS REQUIRED FOR UNEQUIVOCAL LOCATION OF OIL ZONES IN SANDSTONES

Porosity of Formation	F for $m=1.9$	F for $m=1.4$	Oil Not Detectable Unless Water Saturation Less Than:	
			$n=2.0$	$n=1.7$
0.10	80	25	56%	50%
0.15	38	14.5	61%	56%
0.20	22	9.5	65%	60%
0.25	14.5	7	69%	65%
0.30	10	5.4	73%	69%

If an expression of the form of Equation (2) is used, it seems reasonable to expect a higher degree of precision. It will be assumed here that the best average expression for sandstone reservoirs in the United States is close to $F=1.25\ \phi^{-1.61}$.

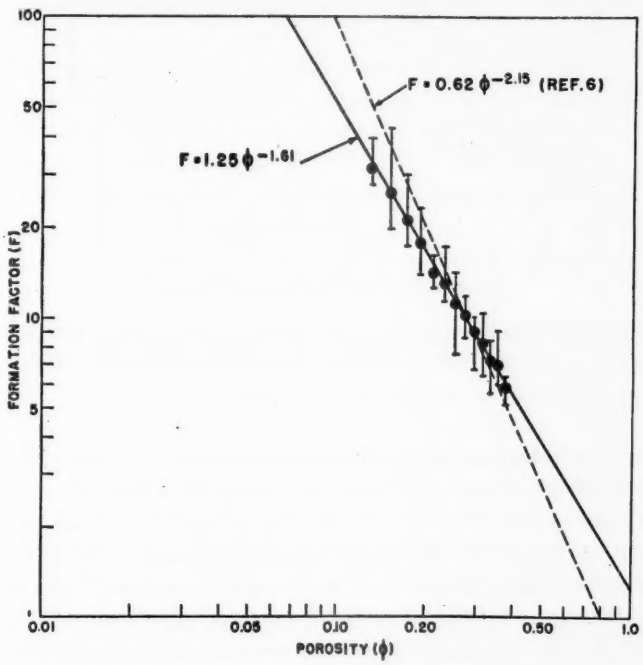

FIG. 2. Best formation factor-porosity relationship for sandstones using all available data (approx. 1,500 measurements) on sandstone cores from Texas, Mississippi, Louisiana, Oklahoma and California.

This expression is based on the average of formation factor and porosity data obtained on some 1,500 samples from the Gulf Coast, Mid-Continent, and California. It is not suggested that $F = 1.25\phi^{-1.61}$ is necessarily the best relationship between formation factor and porosity in any particular area. Nevertheless, for the general case where the formation is known to be a sandstone but no further information concerning the relationship between formation factor and porosity is available, $F = 1.25\phi^{-1.61}$ may be used. If, in a particular area or for a particular

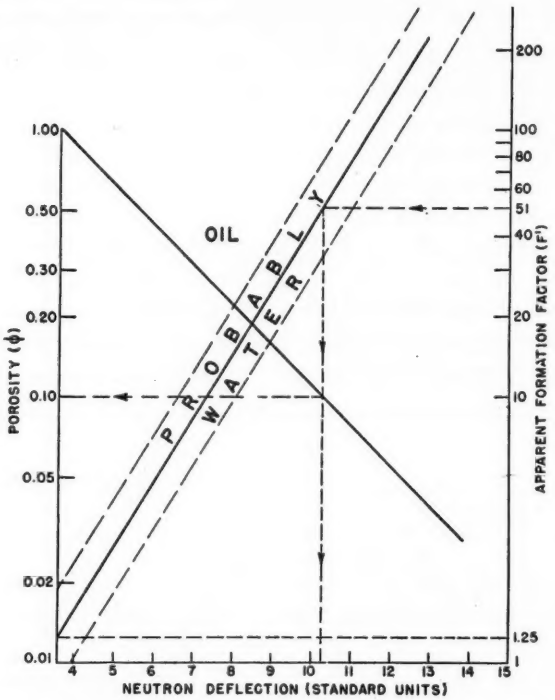

FIG. 3. Method of plotting apparent formation factors against neutron deflections to estimate oil saturation and to determine the porosity neutron deflection calibration when $F = 1.25\phi^{-1.61}$ in sandstones.

formation, a better relationship has been established, the established relationship is to be preferred. Figure 2 shows the data on which the relationship $F = 1.25\phi^{-1.61}$ is based. The vertical lines show the limits of spread of the average values of formation factor for different formations at each of the porosities, while the shaded points indicate the over-all arithmetical average formation factor at each porosity. On Figure 2 the expression $F = 0.62\phi^{-2.15}$ is drawn as a dashed line.

The data of Figure 2 reveal that on the average plotted apparent formation factors of water-bearing sands will not be displaced above or below the line corresponding to $F = 1.25\phi^{-1.61}$ by a factor exceeding about 1.5. In this connection,

it may be observed that the formation factors which are plotted from electric log data are the averages of rather large volumes of rock and may therefore be expected to approximate to the average values plotted in Figure 2 rather than to the more widely scattered data derived by numerous measurements made on tiny core plugs. On the assumption that an apparent formation factor will not be displaced from a line corresponding to $F = 1.25\phi^{-1.61}$ by more than ± 1.5, the probability that a point corresponding to a water-bearing sand will fall outside the limits delineated on Figure 3 by dashed lines becomes very small.

The saturation limits for unequivocal interpretation of zones of oil saturation based on these dashed lines, for which the error in F is ± 1.5, are given in Table III. These saturations have been computed for two values of resistivity index exponent, n, viz,. 2.0 and 1.7, and are not porosity dependent.

TABLE III

WATER SATURATIONS FOR UNEQUIVOCAL LOCATION OF OIL ZONES IN SANDSTONES USING $F = 1.25\phi^{-1.61}$

Porosity	Possible F Error is:	Oil Not Detectable Unless Water Saturation Less Than	
		$n=2.0$	$n=1.7$
Independent	± 1.5	67%	62%

Figure 3 shows that the neutron deflection-porosity calibration curve may also be readily established. If $F = 1.25\phi^{-1.61}$, the neutron deflection corresponding to a formation factor of 1.25 corresponds also to a porosity of unity. A formation factor of 51 now corresponds to a porosity of 0.10. Other points on the neutron deflection-porosity curve may be established similarly, and the entire neutron deflection-porosity calibration curve drawn.

APPLICATIONS OF THE BASIC METHOD

The foregoing discussion reveals the basic rationale of what may be called the F'-n interpretation procedure. Modifications to this procedure to suit particular cases should readily be apparent. Some of the more important of these modifications may be briefly outlined.

If, for example, the salinity of the interstitial water cannot be found from the S.P. curve with any precision (for example, when logging in hard formations with a very low resistivity mud) the procedure outlined above may be modified so as still to permit the location of zones of oil saturation and even the estimation of the extent of the saturation. However, unless apparent formation factors can be calculated it is not possible to establish the porosity-neutron deflection calibration curve.

Assuming the the S.P. curve is sensibly flat, it may be assumed that the interstitial waters in the various formations do not differ greatly in salinity. If this is

so, the actual formation resistivities may be plotted against the appropriate neutron deflections, and oil saturation attributed to formations corresponding to plotted points having higher ordinates than average. As before, resistivity indices will be given by the ratio of the ordinate of the plotted point to the average ordinate at the same neutron deflection.

In this type of plot, if a neutron deflection-porosity calibration has been established from core analysis data for the appropriate borehole size and formation type, the best average line through the plotted resistivity-neutron deflection data which appear to correspond to water-bearing formations may be extrapolated to cut the porosity ordinate. Then the value of this intercept, read on the parallel resistivity ordinate scale, will be equal to the resistivity of the interstitial waters in the formation if carbonate rocks are considered and Equation (1) used. For sandstones, assuming that $F = 1.25\phi^{-1.61}$, the intercept will be equal to 125 percent of the average interstitial water resistivity. These constructions are readily appreciated. If interstitial water resistivity is constant, the resistivities of water sands are related to their formation factors by a constant factor, the interstitial water resistivity. When porosity is unity, formation factor will be either unity or 1.25; the former if Equation (1) is used, the latter if Equation (2) for $c = 1.25$, $k = 1.61$. Hence, the resistivity at a porosity of unity will be either the interstitial water resistivity or 125 percent thereof.

In the analysis of logs run in oil-base mud the combination of induction log and neutron log data is invaluable. Under such conditions, only the problem of estimating connate water resistivity remains outstanding. If the connate water resistivity of one water sand of appropriate matrix type is known, the interpretation will be greatly facilitated, although it may still involve assumptions. Alternatively, it may be possible to construct a porosity-neutron deflection calibration from core analysis data. Whether the calibration is made from log data or core analysis data, it will enable other sections of the hole, where the borehole diameter is the same and formation type similar, to be better interpreted. By suitable plotting it will be possible to establish, as discussed above, the interstitial water resistivity of water sands. If, however, a sand is erroneously believed to be water-bearing when in fact it contains oil, a spurious water resistivity will be calculated. This water resistivity will be greater than the true figure by a factor equal to the resistivity index of the formation. If water resistivities adjacent to the oil-bearing formation are reasonably constant and geological considerations favor such consistency, the anomalously high interstitial water resistivity may immediately suggest the probability of oil saturation.

Another interpretation procedure applicable only to rather thick formations is the possibility that the plot of resistivity against neutron deflection for an oil-bearing formation will give a much less consistent trend than that given by a corresponding water-bearing formation. This seems probable because in an oil-bearing formation resistivity is not only controlled by formation factor and interstitial water resistivity, but also by the resistivity index. The latter is de-

pendent upon the magnitude of the irreducible water saturation and the resistivity-index exponent, both of which may vary considerably even when formation factor and porosity are rather constant (8).

Practical Considerations

The foregoing discussion implied that neutron curve data are always consistent and accurate and that true resistivities are easily determinable from logs. In practice, neither implication is ever completely justified.

It is not the intention of this discussion to suggest means whereby the accuracy of neutron and electric logging instruments can be improved. There is little doubt, however, that technical improvements are to be expected in both types of log. However, with present logging equipment it is extremely desirable that neutron and electric logs be simultaneously recorded since the difficulty inherent in matching a neutron log and a resistivity log run in the same hole at different times is often surprisingly great.

Since neutron logs as at present recorded are acutely sensitive to variations in borehole diameter, the application of the F'-n interpretation technique should at present be limited to conditions where holes stay to gauge. Generally speaking, constant diameter boreholes are obtained when drilling takes place in oil-base mud or through clean limestones and dolomites. It is in the interpretation of logs run in such holes that the F'-n method should be most helpful, particularly since carbonate rocks generally show a desirably wide range of porosity. In oil-base mud logging, the simultaneous running of neutron and induction log surveys should be undertaken in the uncased hole. In oil-base mud both these logs are peculiarly well-adapted to the conditions, since neither requires any direct contact, electrical or otherwise, with the formations. Again, in an oil-base mud, since there is no borehole conductivity and a minimum of filtrate invasion, the induction log may be expected to give apparent resistivities which closely approximate true resistivities, unless the formations are extraordinarily thin.

In the logging of limestone and dolomite formations, it is already common practice to determine porosity from the neutron log using core analysis information to calibrate the log. The difficulty in this type of formation is to obtain good approximations to the true resistivity of quite narrow slices of formation. The newer types of focusing logs, such as the Laterolog (2), enable this difficulty to be overcome in many instances. However, in the case of water-bearing zones the ratio of the Laterolog apparent resistivity to the true formation resistivity is very sensitive to the resistivity of the invaded zone (9). Since the discrimination of oil-bearing from water-bearing zones by the F'-n interpretation procedure requires that the apparent resistivities of the water-bearing zones be not unduly greater than their true resistivities, it would seem that the method will at least be qualitatively successful when the mud resistivity is not greater than about twice the interstitial water resistivity. This condition obtains almost unavoidably in such areas as Kansas. Where the mud resistivity tends to be high and cannot

be lowered without considerable and expensive mud treatment, it would seem desirable, as in oil-base mud logging, to run simultaneous neutron and induction log surveys.

THE PROBLEM OF DIRTY FORMATIONS

Carbonate rock reservoirs are in many cases relatively free of contamination by shales and clays, but this is not true of many good sandstone reservoirs. Application of the F'-n interpretation procedure to shaly reservoirs will involve two errors which, although qualitatively compensatory in their effects, are scarcely likely to give rise to no total error. A formation which contains laminations of hydrogenous solids, such as shales or clays, will show a spuriously high porosity on the neutron curve and give a spuriously low resistivity. Here spurious is used in the sense that the reservoir formation between the shale or clay laminations is presumed to be clean and to have a smaller porosity and a greater true resistivity than the average quantities indicated by the neutron and resistivity logs. If the shale or clay is disseminated throughout the reservoir formations, its effect on the log curves is qualitively similar to that of laminations, although the mathematical treatment of the problem is different.

It seems justifiable to apply to the solution of this problem data from the other common radioactivity logging curve, the gamma-ray curve (3). This curve seems to respond primarily to the natural radioactivity of that part of the solid matrix of formations which is both hydrogenous and electrolytically conductive. It is necessary that assumptions be made for which the sole present excuse is that they are not inherently unreasonable. Nevertheless, it is emphasized that this discussion is largely speculative and intended only to suggest further lines of attack on what is perhaps the most complex and difficult problem in log interpretation.

If the fraction of shale or clay in a laminated formation is p, the fraction of the formation which is clean is $(1-p)$.

Then, if R_{ta} is the apparent average formation resistivity from log data, R_t, the resistivity of the clean formation and R_{sh} that of the shale:

$$\frac{1}{R_{ta}} = \frac{p}{R_{sh}} + \frac{1-p}{R_t}. \tag{4}$$

Equation (4) can be solved for R_t only if p and R_{sh} are known. Considering the latter parameter first, as an approximation a resistivity may be attributed to R_{sh} identical to that of shale sections adjacent to the laminated bed.

To obtain the shale fraction, p, it is necessary to assume not only that the electrical properties of the laminated shales are identical to the properties of adjacent shale sections, but that their natural radioactivity per unit volume is identical. This assumption is probably most accurate when the maximum gamma-ray deflections opposite shale beds are very similar above and below a laminated bed.

A graph may then be plotted on linear coordinates with p from zero to one as ordinate and gamma-ray deflection measured from the clean, shale-free, line (3) as abscissa. On this graph the average deflection opposite shale is plotted against $p = 1.0$ and the minimum deflection for clean sands against $p = 0$. These points may be joined by a straight line and the shale fraction, p, in the laminated formation determined for the average gamma-ray deflection opposite the laminated formation. That this method of construction may be expected to yield reasonable values for p in spite of the somewhat different densities and hence gamma-ray absorption coefficients of pure shale and laminated sand-shale sequence is supported by the recent data of Mardock and Myers (10) for the Sprayberry formation of West Texas.

If developments directed to the perfection of a device for measuring the resistivity of the filtrate-invaded zone of a formation are successful, it will be possible to write:

$$\frac{1}{R_{xo}} = \frac{p}{R_{sh}} + \frac{1 - p}{FR_{mf}} \tag{5}$$

where R_{xo} is the resistivity of the invaded zone, R_{mf} that of the mud filtrate and the other symbols have the same significance as before. From Equation (5) it will be possible to estimate F, although this value will be somewhat high if the formation is oil-bearing owing to the presence of oil not displaced by mud filtrate. Nevertheless, using this value of F and a value of R_t from Equation (4), it will be easier to make a qualitative estimate of the likelihood and possible magnitude of oil saturation in a shaly formation.

In the important case of shaly sands drilled with oil-base mud no measurement of R_{xo} is feasible. Application of the F'-n method must be resorted to using the value of R_t from Equation (4) to compute F'. Since the presence of shale will affect the neutron curve in such a manner as to increase the apparent formation porosity, this method will tend to overestimate the probability of oil saturation. However, knowledge of p together with experience and data bearing on the porosity of shales at various depths (11, 12) and their neutron interactions may enable a reasonable correction factor to be applied to the apparent porosity derived from the neutron curve. It is evident, however, that the number of variables involved in the interpretation of logs of shaly formations makes their interpretation unusually complex and difficult. Nevertheless, if data from two logs as dissimilar in type as the electrical and radioactivity are combined, it is reasonable to expect that a contribution will be made to the solution of the problem which will exceed that resulting from the use of each log separately.

SUMMARY

It is suggested that since the neutron log reflects in large measure the porosity of a formation, data from this log may be used directly to define, at least within limits, the formation factor of porous rocks. Since the determination of formation

factor represents one-third of the problem of interpreting electric log records, and in some cases the most difficult one-third, the use of neutron logs in this manner materially facilitates electric log interpretation. This is particularly true when logging in oil-base mud or in carbonate rock formations. Accordingly, it is suggested that resistivity logs of the focusing type should be run in the open hole at the same time as neutron logs.

By introducing the concept of the neutron deflection that corresponds to a formation factor of unity, it is shown that it is in principle possible to calibrate the neutron log in terms of porosity without recourse being made to the results of core analysis. Each such calibration is only valid for boreholes of a particular size and for formations having matrices of a particular chemical type. The fact that larger volumes of rock are integrated by neutron and resistivity logs than are considered in core analysis may render this type of calibration preferable to that used at present, in spite of the assumptions that must be made regarding the form of the formation factor-porosity relationship. In sections where the porosity is of the fracture type, the fact that porosity measurements are being made under overburden pressure when the F'-n technique is used may contribute considerably to their realism vis-à-vis core analysis.

The problem of the interpretation of electric and radioactivity logs of shaly formations is briefly considered. It is shown that the interpretation of logs of such formations is a peculiarly complex problem, but that the use of both gamma-ray and neutron logs in close association with electric logs may contribute significantly to better qualitative interpretations.

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The writer is indebted to Dr. Paul D. Foote, Executive Vice President, Gulf Research & Development Company for permission to publish this paper.

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THE INTERPRETATION OF ELECTROMAGNETIC REFLECTION DATA IN GEOPHYSICAL EXPLORATION PART II.—METALLIC MODEL EXPERIMENTS*

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ABSTRACT

A metallic model of a horizontally stratified section of the earth's crust has been constructed to provide information of considerable value in the interpretation of geophysical data. Modeling considerations and experimental arrangements are discussed in detail for a system employing loops of wire as transmitter and receiver for the study of propagation of electromagnetic energy in and on a semi-infinite conductor. An experimental check of the theory given in Part I (Yost, 1952) has been made for the case of a semi-infinite conducting medium underlying a semi-infinite insulator. Discontinuities in electrical conductivity within such a medium have been shown to reflect electromagnetic pulses back to the surface. A detailed study of the shape of these pulses from single reflectors has been made showing that certain characteristics of the pulse shape can be correlated with the depth and nature of the reflecting horizon. The reflected signals can be approximately described by considering the discontinuities as reflectors which, in turn, can be replaced by virtual "image" oscillators in a homogeneous structure. The extent to which this approximation holds is discussed in the light of experiments with the model. An example is given of the use of a non-concentric loop arrangement for geophysical profiling of a limited reflector, such as a salt dome. Finally, data are given to show the agreement between model signals and field results obtained from a known resistivity contrast in the earth.

I. INTRODUCTION

In Part I of the present series of papers (Yost 1952),‡ all of the equations governing the propagation in and on a semi-infinite conductor were expressed in terms of a quantity, ξ, called the numerical distance. This quantity was defined in 5, Part I, as 2π times the distance, where the latter was expressed in wavelengths within the conductor. Hence, as was pointed out, these equations determine the electromagnetic fields in geophysical experiments in the sedimentary section just as well as in any other conducting medium, such as a metallic system. If two such conducting media can be chosen so that the values of ξ appearing in both of them are identical, then identical results will be obtained. In this sense, one has a model whenever one system is much smaller than the other, which is exactly the situation to be described in this paper. A small laboratory model has been constructed and used to provide an experimental check of the theory in Part I, to assist in the interpretation of geophysical field experiments, and to obtain more detailed information concerning electromagnetic reflections than can be obtained by either field experiments or theoretical computations. This work clearly demonstrates that discontinuities in electrical conductivity in a medium such as the earth can reflect electromagnetic pulses back to the surface. The at-

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‡ This will be referred to as Part I in the remainder of the present paper.

tenuation and dispersion drastically alter the shape of such pulses but always in a manner predicted by the theory of such processes.

The use of models of electromagnetic systems has been rather extensive in the study of the fields near antennas used for radio frequency transmission and reception (Brown and King 1934); (Sinclair 1948). However, for studying signals of the type that would be encountered in geophysical prospecting, the use of scaled models has been limited. Model experiments of the response of conducting bodies in an electromagnetic field have been reported by Slichter (1932) and by Clark and Mungal (1951). Slichter showed close agreement between the theoretical response and that observed with models for a conducting sphere in the inductive field of a vertical exciting loop and also observed the model response of a plane rectangular conductor in the same field. Clark and Mungal used a horizontal exciting loop and observed the deformation of the phase and amplitude of the magnetic field at points within the loop when positioned over a conductor. The results indicated how the position, dimensions, and dip of buried conductors in the earth might be evaluated from the model results.

The model described in this paper has some features in common with these earlier models. However, the basic purpose of the present work was to investigate electromagnetic propagation along and into semi-infinite conducting media. Consequently, many features of the present model are different and these are fully described in the following section. Some of the data obtained with this model were of such nature as to provide a direct check upon the theoretical results. They were, therefore, included in Part I with the theory. But, since the theory developed there dealt only with a semi-infinite, homogeneous conductor, it would not deal directly with discontinuities. Instead, it was assumed that discontinuities could, approximately, be considered as reflectors which, in turn, could be replaced by virtual, "image" oscillators in this homogeneous structure. Such an approximation proved very helpful in interpreting geophysical data. However, with this metallic model, it was possible to determine just how good this approximation was. The differences between signals from "image" oscillators embedded in the metallic model and those from reflections caused by discontinuities are presented and discussed. The description of the former is completely given by the earlier theory, but that of the latter must remain in the empirical form given here until the theory of this reflection process has been reduced to a form suitable for comparison with experimental data.

II. MODELING CONSIDERATIONS

The condition for scaling electromagnetic phenomena in different conducting media, the earth and the laboratory model in the case of geophysical prospecting, is that:

$$\frac{R_E^2 f_E \mu_E}{\rho_E} = \frac{R_M^2 f_M \mu_M}{\rho_M} \tag{1}$$

where the subscripts "E" and "M" denote the earth and the model, respectively, R = distance, f = frequency, μ = magnetic permeability, and ρ = electrical resistivity. This relation follows from Stratton's general condition for similitude (Stratton 1941) when it is assumed that there are no significant displacement currents in either conducting medium. A full discussion of the justification for and consequences of this assumption has been presented in Part I. For non-magnetic materials, the usual case, μ_E can be considered equal to μ_M. The distance scaling factor between the earth and the model, R_E/R_M (denoted as S for convenience), was chosen as 12,000/1, i.e., 12,000 inches or 1000 feet on the earth is represented by 1 inch on the model. Thus, with S constant, the problem becomes one of modeling the ratio f/ρ such that

$$\frac{f_M \rho_E}{f_E \rho_M} = 1.44 \times 10^8.$$

In order to be able to use in the field the same instrumentation developed for the model work f_E and f_M were both always within the range of 1 to 10 cycles per second. Therefore, modeling was accomplished principally by proper choice of the ratio of resistivities ρ_E/ρ_M. For example, suppose field data are to be taken at 5 cps over an earth of 50 ohm-feet resistivity so that $f_E/\rho_E = 0.1$. With aluminum plates of a resistivity 0.14 micro-ohm-feet the model would be operated at 2.02 cps to simulate the field data. On the other hand, with magnesium plates of 0.6 micro-ohm-feet resistivity the model would be run at 8.64 cps.

While the above considerations regarding proper modeling assure the exact similarity between the prototype and the model, they do not specify the relation between the magnitude of the quantities to be experimentally measured. This can best be done by examining the dimensional terms in the expression for the measured voltage (Equation 21, Part I). From this, one finds that:

$$V \propto \frac{A_t A_r N_t N_r I f}{R^3} \tag{2}$$

where V is the amplitude of the measured voltage; A_t and A_r are the areas of the transmitter and receiver, respectively; N_t and N_r are the number of turns in these same coils; I is the amplitude of the transmitter current; and the other quantities are the same as in Equation (1). Since the ratio of prototype coil area to model coil area is S^2 for each loop, the voltage ratio (model to earth) is:

$$\frac{V_M}{V_E} = \frac{1}{S} \frac{f_M}{f_E} \frac{N_M^2}{N_E^2} \tag{3}$$

where $N = N_t = N_r$ for both model and earth. Therefore, if f_M is approximately the same as f_E, it is necessary that $N_M^2 = S N_E^2$ in order to have comparable voltages in the earth and model cases. This was accomplished, approximately, by having $N_M = 100$ and $N_E = 1$ for the work reported here.

The loops were flat, circular spirals of wire and were always parallel and adjacent to the horizontal, smooth metallic plate surfaces. The currents induced in the metal plates flow in horizontal planes so that a stack of plates acts as a homogeneous region provided that there are no lateral changes in resistivity within individual plates and provided that all plates have the same resistivity. Experimental confirmation of the correctness of this concept was established by the identical signals obtained from a thick single plate of aluminum and from a stack of plates of the same resistivity and the same total thickness. Also, when a horizontal loop was placed on top of a stack of vertical plates, transmission through the medium vanished because the thin vertical air films interrupted the current trying to flow in horizontal planes.

TABLE 1

RESISTIVITIES OF METAL PLATES

Metal	Resistivity Ohm-ft
Copper	$.0569 \times 10^{-6}$
Aluminum I	$.141 \times 10^{-6}$
Aluminum II	$.120 \times 10^{-6}$
Aluminum III	$.192 \times 10^{-6}$
Aluminum IV	$.134 \times 10^{-6}$
Dow Metal (90% Magnesium)	$.60 \times 10^{-6}$
Lead	$.743 \times 10^{-6}$
Stainless Steel	2.33×10^{-6}
Iron	$.412 \times 10^{-6}$
Nickel	$.317 \times 10^{-6}$
Monel	1.49×10^{-6}

III. EXPERIMENTAL ARRANGEMENT

The model consisted of a stack of square metallic plates each 24 inches on a side and of uniform thickness and resistivity. Rolled plates of aluminum of thicknesses 0.5 to 3 inches and aluminum castings 4 and 5 inches thick and Dow metal (90 percent magnesium) castings 4 and 5 inches thick were used to form homogeneous "models." Reflectors having a wide range of resistivity values were obtained by the use of lead, copper, stainless steel, iron, monel, and nickel of various thicknesses. Table 1 gives the resistivities of the metal plates used. Aluminum plates from several different sources had various resistivities and are listed in the table as aluminum I, II, III, and IV. A stack of plates forming a model was tightly clamped together in order to reduce the small air gap between adjacent plates. Otherwise, such gaps would act as thin, high resistivity reflectors.

Two different types of loop arrangements were used: (1) non-concentric loops wherein the two loops were identical, each consisting of 100 turns of number 30 enameled copper wire in two layers; the mean diameter of each loop was one inch and the separation between centers of loops was variable, (2) concentric loops wherein the potential or receiving loop consisted of 10 turns of number 30 enam-

eled copper wire and the current or transmitting loop consisted of 10 turns of number 24 wire. The mean diameter of the potential loop was one inch and the current loop diameter was five, ten, or fifteen inches. The important point is that the coils must be as thin as possible in order to obtain good coupling to the aluminum plates.

As discussed in Part I, all essential information in this type of work can be obtained from a single, sharp transient applied to the transmitter. However, for ease of display on a cathode ray oscilloscope and for noise suppression, regularly repeated current pulses are desirable. Current pulses of excellent square-wave form were obtained by use of a mechanical commutator and relay system. An 1,800 rpm synchronous motor was geared down to a selected speed in the range 2 to 10 cps to operate the mechanical contacts which closed the circuit containing the coil of a relay* whose mercury contacts were capable of handling 6 amperes of current supplied to the transmitting loop on the model. On the shaft that operated the mechanical contactor was mounted a 72-tooth steel spur gear as a generator of timing markers. A coil having 250 turns and a permanent magnet core were mounted so that the teeth of the gear passed close to the extended tip of the core. The e.m.f. generated in the coil was amplified and used to drive a square wave generator whose output was connected to the Z-axis input of the oscilloscope. The signal from the receiving loop on the model was amplified 20 times by a special transformer† which yielded a noiseless voltage gain. The transformer secondary was connected to the input of a high gain amplifier having a good low frequency response. The output of the amplifier went to a compensating filter to restore the low frequency square wave response lost in the transformer then to a special 60-cycle filter and finally to the input of a Dumont Type 304-H oscilloscope. All signals were recorded for measurement by photographing the oscilloscope screen. The timing markers, applied to the Z-input of the oscilloscope, intensity-modulated the trace appearing on the oscilloscope screen. Thus, a time reference was provided for each portion of the received signal relative to the time of generation of the current pulse causing the signal. This time is given in terms of fractions of a cycle of one current pulse (degrees), rather than in terms of seconds, because of the manner in which the timing markers are obtained. Accordingly, for each signal shown in the accompanying figures, the time axis is given in degrees, where one complete cycle is 360 degrees and the current pulse is usually 180 degrees. The repetition frequency is also stated so that time in seconds of any part of a signal, say of the peak of a reflected signal, can be easily determined. For example, if a reflected signal peak occurs at 20 degrees and the pulsing frequency is 2.04 cycles per second, the peak occurs at a time 27.2 milliseconds after initiation of the current pulse.

To study signals from a homogeneous model earth one stack of metallic plates

* Western Electric Company, Type D-168479 Relay.

† Southwestern Industrial Electronic Company, Houston, Texas, Type D-116.

was used. However, to study the signal from a reflecting layer (resistivity contrast) embedded in an otherwise homogeneous earth two models were used. One model was homogeneous and the other model contained the reflecting layer. Since both models produced the same homogeneous, or boundary wave, signal, the difference between the two was due only to the reflecting layer. The current loops on the two models were in series and the potential loops were in series opposition. Hence, the net received signal was that due to the reflector only. (Subtraction of the two signals was performed in the secondary circuits of the transformers.)

III. SURFACE FIELDS (BOUNDARY WAVES) FOR DIFFERENT COIL ARRANGEMENTS

Experimental boundary waves for several concentric loop arrangements and for non-concentric loops separated different distances have been obtained. The loops were parallel and adjacent to the horizontal surface of the metallic model of the earth. Each loop was then a magnetic dipole with its axis perpendicular to the surface. The stack of metal plates was considered infinite in thickness when the effect of adding an additional plate to the bottom of the stack could not be detected in the signal at the receiver loop. For the coil arrangements shown here this thickness was five inches. The corresponding theoretical curves for a semi-infinite, homogeneous conductor were calculated by the methods given in Part I and are here compared with the experimental data for each case.

The non-concentric loop system employed identical current and potential loops each of one inch effective diameter over a homogeneous stack of aluminum plates of resistivity 0.14 micro-ohm-feet. The separation of the centers of the coils was 2.5, 5.0, and 7.5 inches. The data are shown in Figure 1. It is interesting to note that for large separations of loops the boundary wave is negative at large phase. In Figure 2 is shown a comparison of the experimental data for the 5 inch separation of loops with the calculated curve based on magnetic dipoles.

The concentric loop arrangement consisted of transmitting loops of 5, 10, and 15 inches mean diameter with a receiving loop of 1 inch mean diameter as well as the following combinations: 10″-5″, 15″-5″, 15″-10″, and 10″-10″, where the larger diameter loop is the transmitter. The experimental data for four of these combinations are shown in Figure 3. In Figure 4 is shown a comparison between experiment and theory for square concentric loops of 10 and 1 inches on a side, respectively, for the transmitter and receiver. The theoretical curve is based on line integrals of electrical dipoles.

The agreement between theory and experiment for both types of loops is excellent, showing clearly that the field intensities on the surface for a homogeneous conductor are not in-phase with the exciting current. As the distance of separation between current and potential loops is increased, the peak of the boundary wave signal becomes broader, decreases in amplitude and occurs at later times (larger phases on the plots shown).

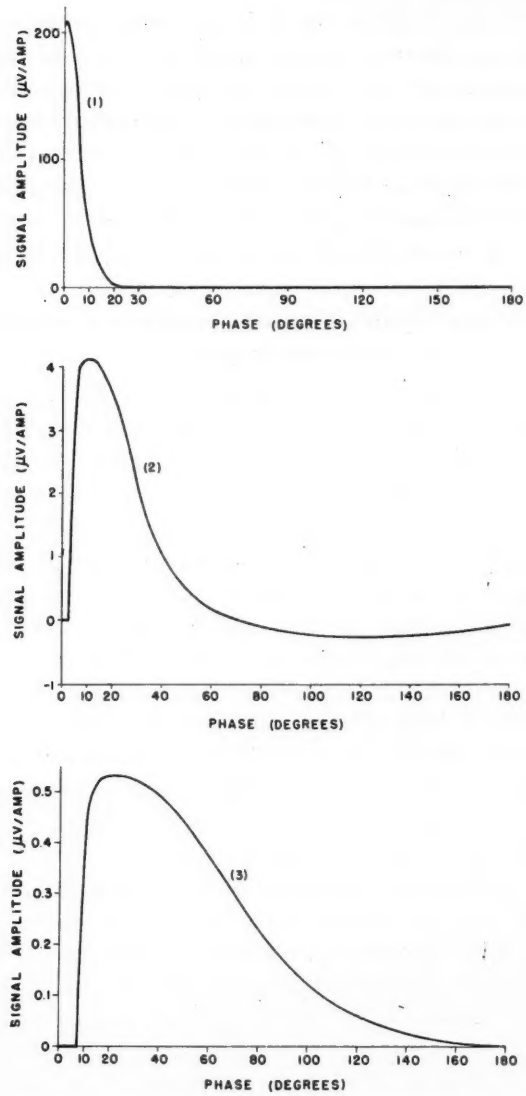

FIG. 1. Boundary Wave for Non-Concentric Loops, Reproductions of Experimental Curves. 1 inch mean diameter loops. 180° current pulse. Frequency 2.59 cps. Aluminum I "model." Separation of centers of current and potential loops are: Curve 1, 2.5 inches; Curve 2, 5.0 inches; Curve 3, 7.5 inches.

IV. REFLECTED SIGNALS FROM A SINGLE REFLECTOR

Using the dual-model scheme to suppress the effects from a homogeneous system, reflected signals from a single reflector were obtained for many different conditions. The procedure used was to set up two identical model "earths," each

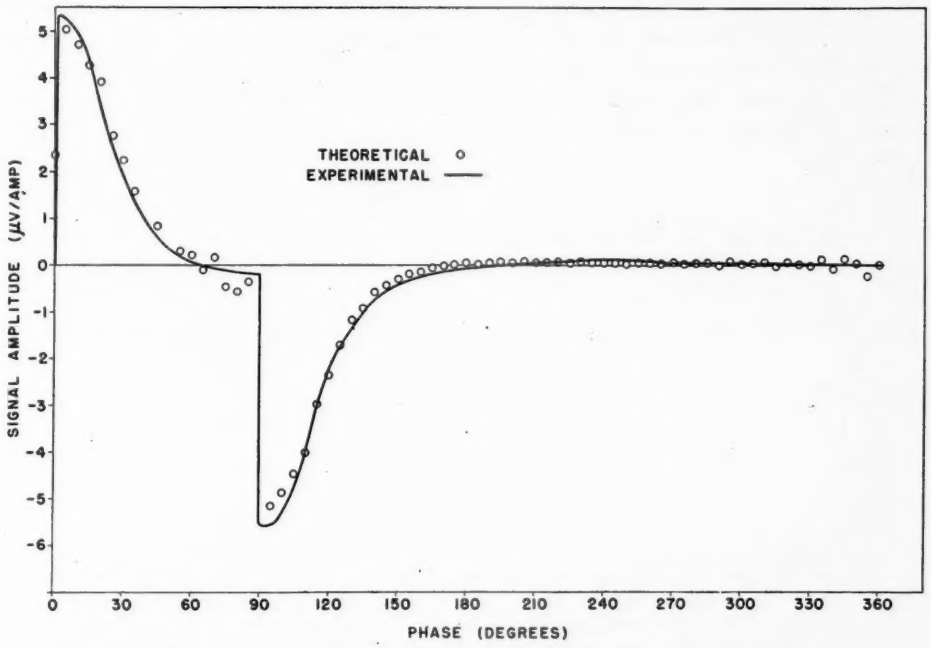

FIG. 2. Boundary Wave for Non-Concentric Loops, Comparison of Theoretical and Experimental Curves. Loops 1 inch mean diameter, 5 inches separation, 90° current pulse. Frequency 2.59 cps. Aluminum I "model." Solid curve is reproduction of experimental photograph; o—computed points based on magnetic dipoles.

a 5 inch thickness of aluminum with a transmitting loop and a receiving loop on the surface. The two transmitting loops were connected in series and hence were energized simultaneously by the current pulses. Thus, a boundary wave was generated on the surface of each block of aluminum. The receiving loops of the two models were connected in series opposition so that the two boundary waves cancelled leaving a straight line trace on the oscilloscope screen.* Now, when a reflector was inserted in one of the models, the reflected signal alone appeared on the oscilloscope screen, as the boundary wave was being automatically cancelled. The reflected signal could then be observed during the entire period of the wave and could be measured accurately. In Plate I are reproduced actual photographs of the oscilloscope traces of: (1) Boundary Wave, (2) Boundary Wave plus Reflected Signal and (3) Reflected Signal for a given loop geometry and model. The advantages of observing only the reflected signal are obvious. The reflected signal

* In practice, a shunt was used across one current loop to reduce the current therein to a slightly smaller value than in the other loop to effect cancellation since the two aluminum stacks were not of exactly the same resistivity. Also, one potential coil could be moved by small amounts with a thumb screw arrangement in order to make the separations of loops comparable on both models.

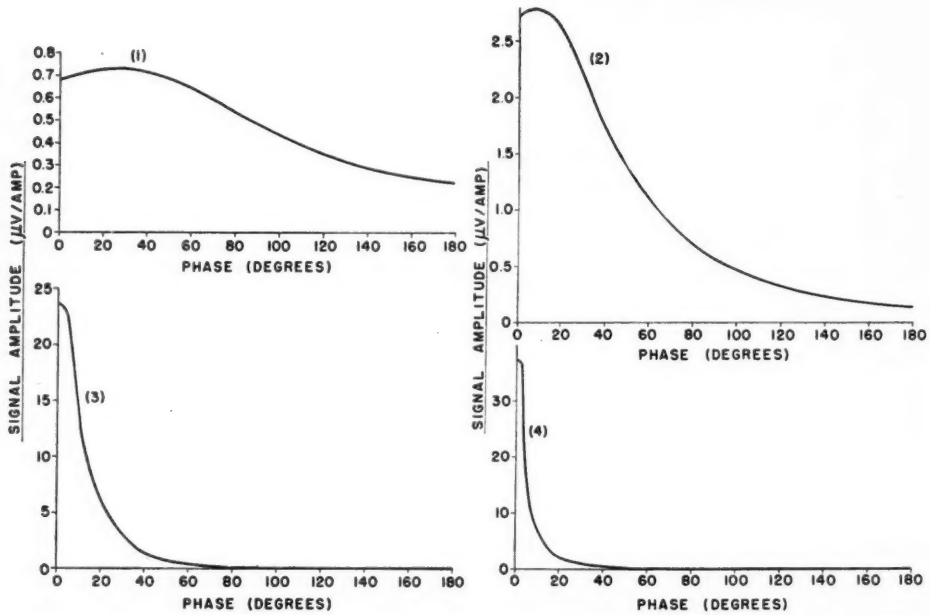

FIG. 3. Boundary Wave for Concentric Loops, Reproductions of Experimental Curves. 180° current pulse. Frequency 2.59 cps. Aluminum IV "model." Diameters of current and potential loops, respectively, are: Curve 1, 15 inches—1 inch; Curve 2, 10 inches—1 inch; Curve 3, 5 inches—1 inch; Curve 4, 10 inches—10 inches.

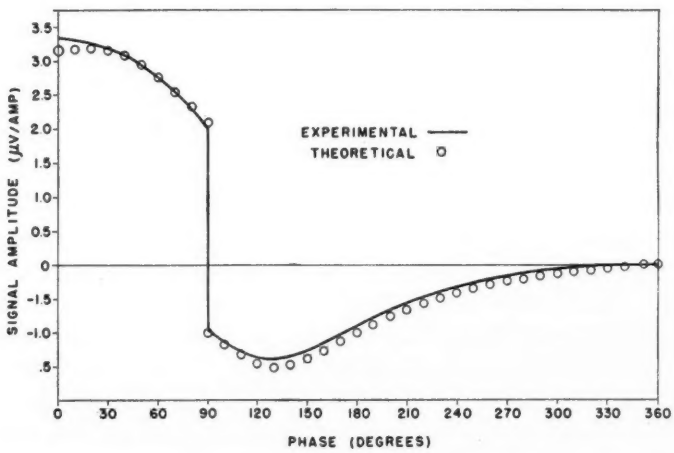

FIG. 4. Boundary Wave for Square Concentric Loops, Comparison of Theoretical and Experimental Data. Current loop 10 inches on a side; potential loop 1 inch on a side. 90° current pulse. Frequency 5.2 cps. Aluminum I "model." Solid curve is reproduction of experimental photograph; o—computed points based on line integrals of electrical dipoles.

shown in Plate I is from a Dow metal (90 percent magnesium) reflector and is typical of all reflectors of resistivity greater than the surrounding model. The first peak of the reflected signal is of the same polarity as the boundary wave at the same phase whereas the second peak of the reflected signal is of opposite polarity. The phase of both peaks increases as the depth of the reflector increases as is seen

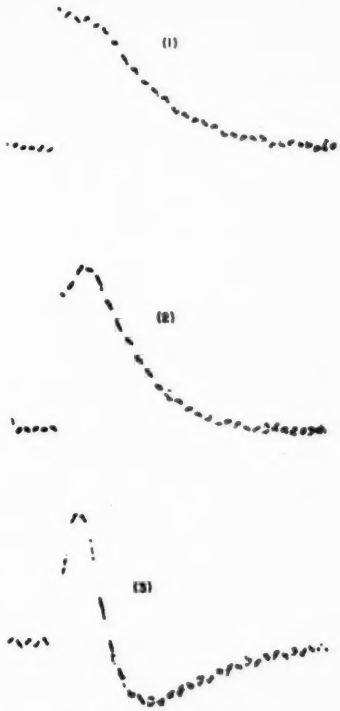

PLATE I. Photographs of the oscilloscope traces of (1) Boundary Wave, (2) Boundary Wave plus Reflected Signal and (3) Reflected Signal for a given loop geometry and an Aluminum I "Model." Reflected signal is from a ½ inch Dow metal plate at ½ inch depth. Amplifier gain is same for (1) and (2), but approximately four times greater for (3).

in Figure 5a, which shows phase shift as a function of depth for a 0.13 inch thick lead reflector in a 0.14 micro-ohm-feet model. Figure 5b shows the reflected signal peak amplitudes as a function of depth for the same lead reflector. Additional data for various types of reflectors are given in Tables 2 and 3. It is interesting to note from Table 3 that air, although possessing an infinite resistivity contrast to aluminum, is only as good a reflector as the non-magnetic stainless steel with its resistivity contrast of 16.5 to 1. That air is not a very good reflector was confirmed by measurements of the transmission through the air gap.

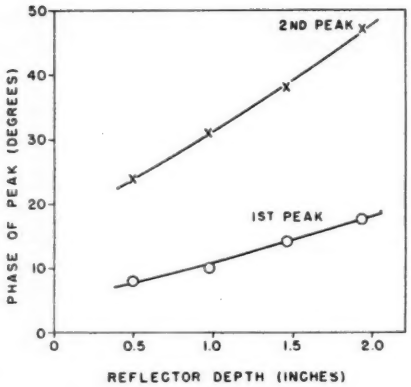

FIG. 5a. Reflected Signal Peak Phase as a Function of Depth of Reflector. Lead reflector 0.13 inch thick. Non-concentric loops 1 inch mean diameter, 5 inches separation. 180° current pulse. Frequency 2.04 cps. Aluminum I "model."

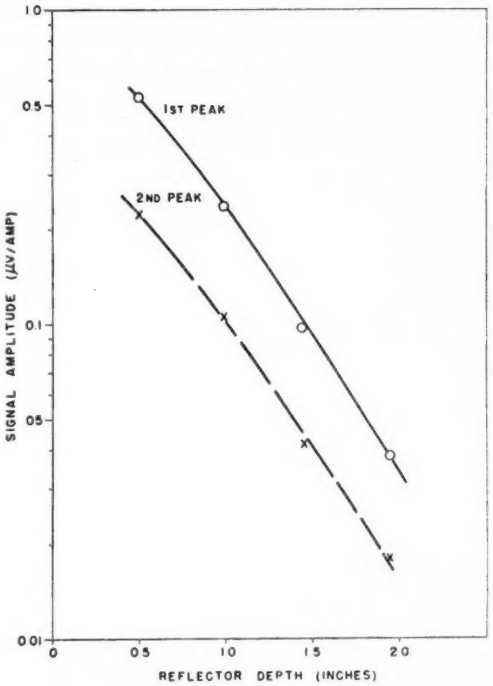

FIG. 5b. Reflected Signal Peak Amplitude as a Function of Depth of Reflector. Same experimental conditions as in Figure 5a.

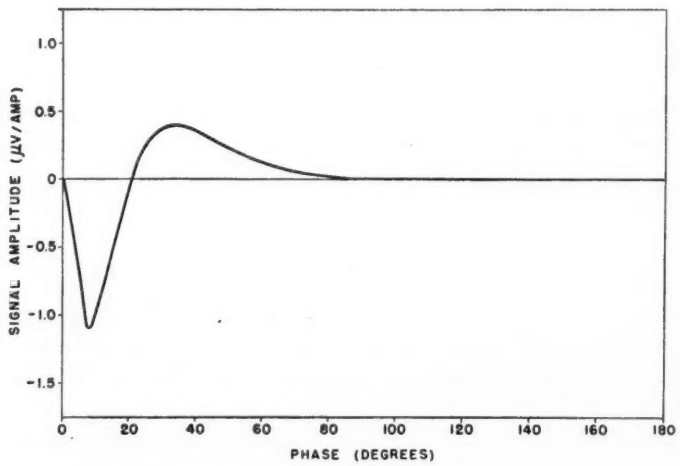

FIG. 6. Reflected Signal from Copper. Non-concentric loops 1 inch mean diameter, 5 inch separation. 180° current pulse. Frequency 5.2 cps. Copper reflector 1 inch thick at 1 inch depth in Aluminum I "model."

When the reflector is of lower resistivity than the surrounding earth, the polarity of the peaks of the reflected signal is reversed. That is, the first peak is of polarity opposite to that of the boundary wave at the same phase. The signal from a $\frac{1}{4}$ inch copper reflector (0.06 micro-ohm-feet) in an aluminum I model (0.14 micro-ohm-feet) is shown in Figure 6.

The reflection from a permeability contrast is shown in Figure 7; the reflector was a 0.14 inch thick iron plate in an aluminum I model. The reflected signals from a magnetic reflector where μ reflector$\gg\mu$ aluminum are of the same polarity as for a reflector of higher resistivity than the aluminum. From Tables 2 and 3

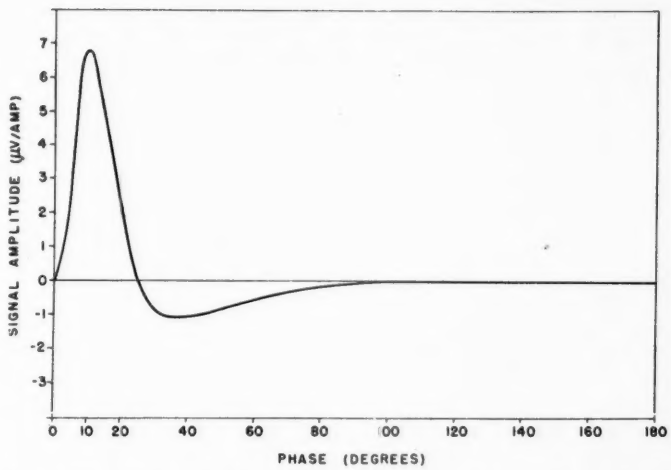

FIG. 7. Reflected Signal from Iron. Non-concentric loops 1 inch mean diameter, 5 inch separation. 180° current pulse. Frequency 5.2 cps. Iron reflector 0.14 inch thick at 1 inch depth in Aluminum I "model."

it can be seen that the three magnetic materials (iron, monel, and nickel) are far better reflectors than the non-magnetic ones, the amplitudes of the first peaks being an entire order of magnitude greater. This fact is of value in obtaining good reflectors for model use. Also, the phases of the peaks of the reflected signals from magnetic reflectors are much greater than for a non-magnetic reflector of about the same thickness and at the same depth.

The effect of increase in thickness of the reflecting layer is demonstrated by the curve of Figure 8. The amplitude of the signal increases as the thickness of the reflector is increased; but the phase of the peaks does not vary markedly with thickness of reflector, particularly for thick reflectors. This near constancy of the phase of peaks is better for non-concentric loops than for concentric loops. An increase in the resistivity contrast produces similar changes to those caused by an increase in thickness of the reflecting layer, as is seen in Figure 9a and 9b. Hence, for single reflectors of resistivity greater than the surrounding model, the

phase of the peak (s) is a measure of the depth of the reflector while the amplitude of the signal depends on the thickness of reflector and on the resistivity contrast.

The ratio of boundary wave signal amplitude to reflected signal amplitude for different loop arrangements is shown in Figure 10a for six concentric loop ar-

TABLE 2

PHASES OF PEAKS OF REFLECTED SIGNALS FROM SIGNAL REFLECTOR AT DIFFERENT DEPTHS ($\frac{1}{8}$ INCH THICK REFLECTORS) IN ALUMINUM I "MODEL"

Depth of Reflector in Inches	Reflector							
	Air	Stainless Steel	Aluminum III	Aluminum II	Copper	Iron	Monel	Nickel
	Phase of First Peak in Degrees							
0.5	8	7	7	7	8	12	11	10
1.0	10	11	11	11	10	17	16	16
1.5	14	14	14		15	22	23	21
2.0	18	19			20	28	25	27
2.5						33	32	31
3.0						35	35	36
3.5						41		
4.0						45		
	Phase of Second Peak in Degrees							
0.5	24	25	27	26	28	37	34	35
1.0	31	32	32	33	34	58	56	55
1.5	38	39	38		40	76	73	75
2.0	47	48			51	86	83	85
2.5						102	100	97
3.0						105	105	102
3.5						114		
4.0						125		

TABLE 3

AMPLITUDES OF FIRST AND SECOND PEAKS OF REFLECTED SIGNALS AND SINGLE REFLECTORS AT DIFFERENT DEPTHS ($\frac{1}{8}$ INCH THICK REFLECTORS) IN ALUMINUM I "MODEL"

Depth of Reflector in inches	Reflector							
	Air	Stainless Steel	Aluminum III	Aluminum II	Copper	Iron	Monel	Nickel
	Amplitude of First Peak in Microvolts/Ampere							
0.5	.638	.600	.139	.068	.579	5.62	6.90	6.14
1.0	.284	.267	.067	.030	.275	2.42	2.80	2.65
1.5	.113	.106	.027		.109	1.13	1.32	1.24
2.0	.041	.042			.039	0.542	.554	.492
2.5							.259	.223
3.0							.105	.0955
	Amplitude of Second Peak in Microvolts/Ampere							
0.5	.278	.256	.052	.024	.233	.917	1.18	..483
1.0	.111	.104	.024	.011	.112	.300	.443	.204
1.5	.050	.047	.011		.060	.200	.272	.152
2.0	.022	.021			.028	.123	.111	.0782
2.5							.0762	.0617
3.0							.0575	.0420

rangements and in Figure 10b for two separations of non-concentric loops. The reflected signals used in constructing these curves were from a ½ inch thick air reflector at different depths. The boundary wave amplitudes were measured at phase points corresponding to reflected signal peaks. The larger phase points correspond to deeper reflections (see Fig. 5a); however, a certain phase does not correspond to the same depth for the different loop arrangements. From Figure

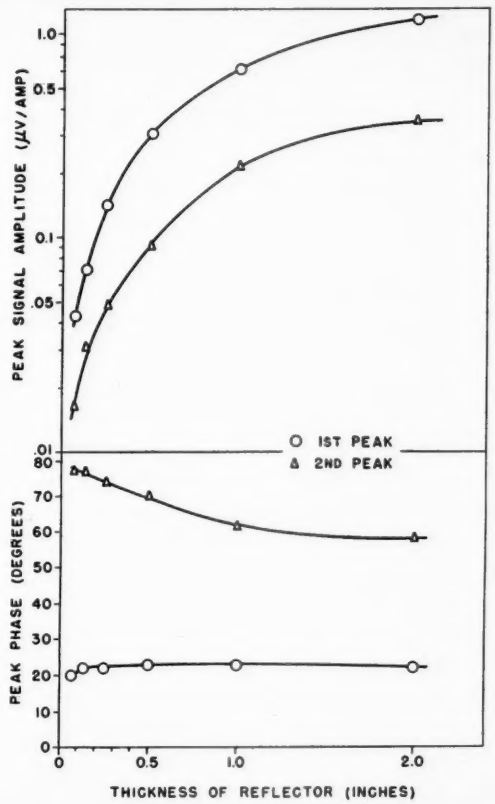

FIG. 8. Reflected Signal Peak Amplitude and Phase as a Function of Thickness of Reflector. Non-concentric loops 1 inch mean diameter, 7.5 inches separation. 180° current pulse. Frequency 2.59 cps. Air reflector at ½ inch depth in Aluminum IV "model."

10b it can be seen that a more favorable ratio of boundary wave to reflected signal (smaller value of the ratio) exists for the second peak of the reflected signal than for the first peak, indicating the usefulness of the second peak for deep reflection studies.

V. VALIDITY OF IMAGE APPROXIMATION

The signals produced when the medium beneath the transmitter and receiver is homogeneous (i.e., the boundary wave) agree excellently with the theory of

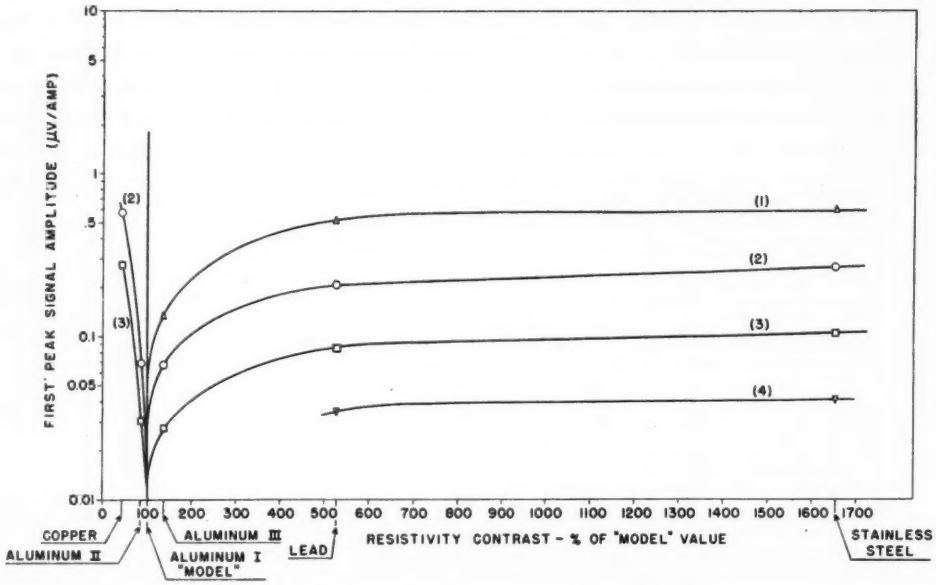

FIG. 9a. Amplitude of First Peak of Reflected Signal as a Function of % Resistivity Contrast of Reflector. Resistivity contrasts are calculated with respect to Aluminum I "model"; the types of plates used are indicated in bottom margin; all plates were ¼ inch thick. 180° current pulse. Frequency 2.04 cps. Curves are for reflectors at various depths as follows:

Curve 1, △ 0.5 inch depth; Curve 2, ○ 1.0 inch depth;
Curve 3, □ 1.5 inches depth; Curve 4, ▽ 2.0 inches depth.

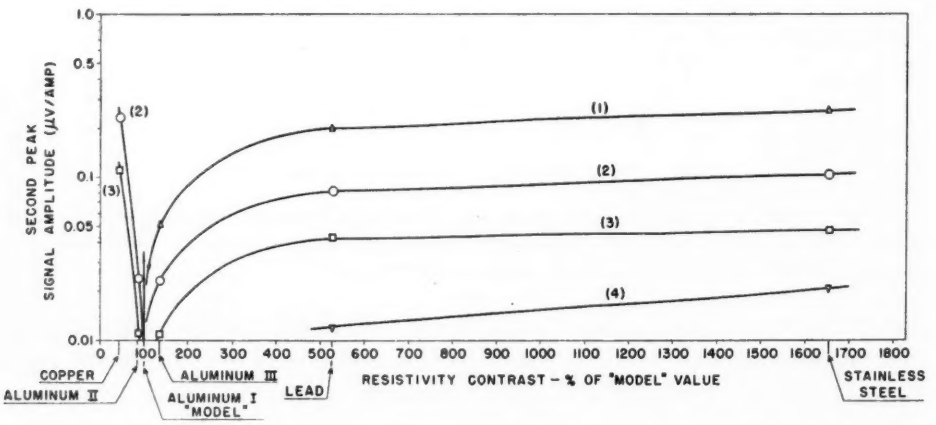

FIG. 9b. Amplitude of Second Peak of Reflected Signal as a Function of % Resistivity Contrast of Reflector. Experimental conditions same as for Figure 9a.

Curve 1, △ 0.5 inch depth; Curve 2, ○ 1.0 inch depth;
Curve 3, □ 1.5 inches depth; Curve 4, ▽ 2.0 inches depth.

Part I. This is true both in the metallic model and the earth as long as either is homogeneous to a sufficient depth. When discontinuities in conductivity or permeability are present, the receiver signal is modified by the addition of a reflected wave. From a single discontinuity of this type, a single reflected signal is obtained as soon as the appropriate boundary wave has been subtracted from the total signal. For data obtained on the earth, this subtraction is accomplished by means of the general curves in Part I. For model data, the subtraction is automatic, as

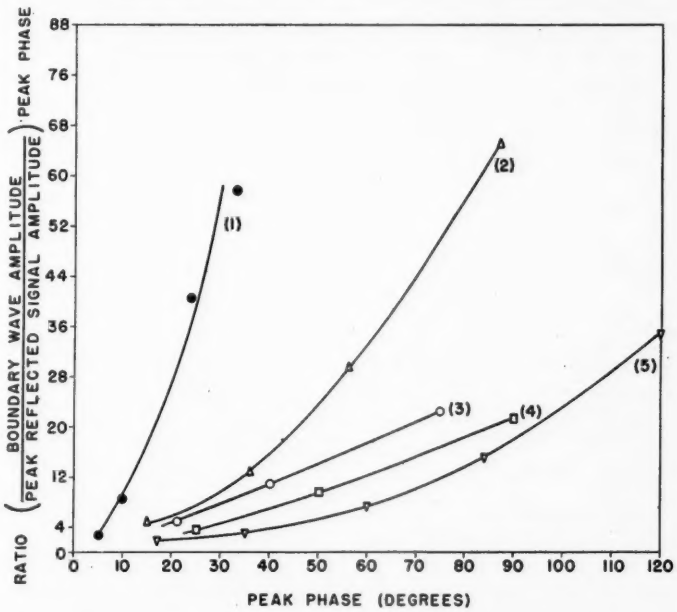

FIG. 10a. Ratio of Boundary Wave to Reflected Signal Peak Amplitude as a Function of Peak Phase of Reflected Signal, Concentric Loops. Mean diameters of current and potential loops, respectively, are:

Curve 1, 5 inches–1 inch; Curve 2, 10 inches–5 inches; Curve 3, 15 inches–10 inches;
Curve 4, 15 inches–5 inches; Curve 5, 15 inches–1 inch.

described in Part IV. In both cases, it has been possible to examine these reflected signals themselves in order to obtain information concerning them.

As indicated in Part I, such reflections from known conductivity contrasts in the earth had the general characteristics of signals transmitted in a semi-infinite conductor and which originated approximately at the image position. This image position was, as in the optical case, vertically beneath the transmitter at a depth equal to twice the depth of the discontinuity. This virtual transmitter had an apparent strength roughly proportional to the percentage change in conductivity at the discontinuity. Hence, in the case of data obtained in the earth, these reflected signals agreed with the transmitted signals from image locations as calcu-

lated. However, these data lacked sufficient precision and the conductivities of earth strata were too inaccurately known for determination of how valid this image approximation was.

The metallic model made it possible to examine this question in considerable detail. As reported in Part I, the model verified the correctness of the transmission theory as a precise description of the signals from image oscillators. Hence, as the model supplied reflected signals and image signals for direct comparison,

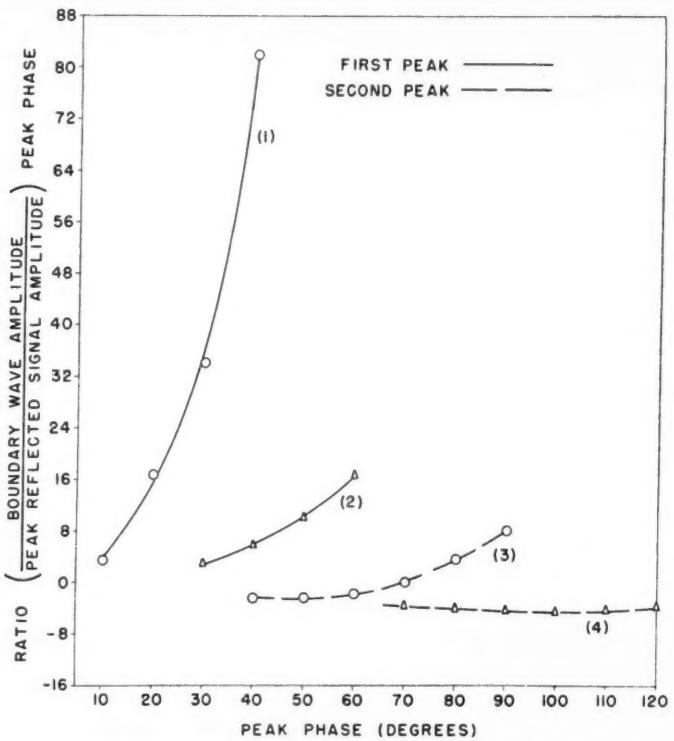

FIG. 10b. Ratio of Boundary Wave to Reflected Signal Peak Amplitude as a Function of Peak Phase of Reflected Signal, Non-Concentric Loops 1 inch mean diameter loops with separation as follows:

Curves 1 and 3—5 inches; Curves 2 and 4—7.5 inches.

it also served as a check on the image theory concept. A comparison of an image signal and a reflection from an imperfect reflector (air) can be made from the curves of Figure 11a. A similar comparison for a nearly perfect reflector (iron) is illustrated in Figure 11b. Both of these were obtained with one of the concentric loop arrangements previously described. More complete data, obtained with non-concentric loops, are summarized in Figures 12a and 12b. In these curves, the peak amplitudes and phase shifts are plotted for different reflector depths as well as different reflector materials (air and iron). The amplitude and phase of

the image signal is included for each depth. From all of these data, as well as reflected data from magnesium, monel, stainless steel, lead, and copper, it is clear that the image concept is only adequate in the case of perfect reflectors (iron, monel, and nickel). In fact, there is an unmistakable trend toward better agreement between reflected and image signals as the product $\mu\sigma$ increases. But, this is as would be expected because of the manner in which $\mu\sigma$ enters the reflection coefficient (see Stratton, 1941, page 512, equation 11). It should be emphasized, however, that the resistivity contrasts within the earth's crust are such that the agreement between reflected and image signals is only a *fair first approximation.*

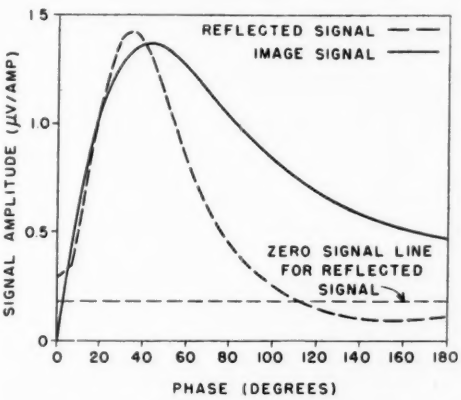

FIG. 11a. Comparison of Image and Reflected Signals, Concentric Loops—Air Reflector. Diameter of loops; current 15 inches, potential 1 inch. 180° current pulse. Frequency 2.59 cps. Aluminum I "model." Solid curve is image signal obtained by transmission through 2 inch aluminum. Dashed curve is reflected signal from thick air reflector at 1 inch depth.

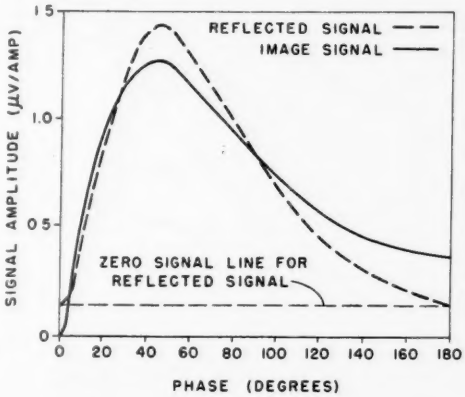

FIG. 11b. Comparison of Image and Reflected Signals, Concentric Loops—Iron Reflector. Same experimental arrangement as Figure 11a, except iron reflector instead of air. Solid curve is image signal obtained by transmission through 2 inches aluminum. Dashed curve is reflected signal from 0.14 inch thick iron reflector at 1 inch depth.

While a more adequate theoretical description of these reflected signals is desirable, the present model provides an excellent empirical description.

One additional set of experiments relating to the reflection process is worthy of mention. For experimental convenience, most reflecting layers studied were of infinite horizontal extent. Yet, the reflection concept suggests that the principal transmission path should be the shortest one from transmitter to reflector to receiver. Hence, experiments were performed with reflectors of various lateral extensions and various locations. In these cases, the type, thickness and depth of the reflector were all kept constant. It was found that a reflector of $1\frac{1}{2}$ inch diameter located midway between 1 inch receiver and transmitter loops 5 inches apart produced a reflected signal of about half the amplitude of the signal obtained from a reflector of infinite lateral extent. With the reflector diameter in-

creased to 5 inches the reflected signal was practically equivalent to the signal produced by a reflector of infinite lateral extent. These experiments thus suggest that the main contribution of the reflected signal is from the area midway between the loops with equal angles of incidence and reflection, plus a small non-specular component. The location of such a limited reflector is important in geophysical profiling and hence is discussed further in the following section.

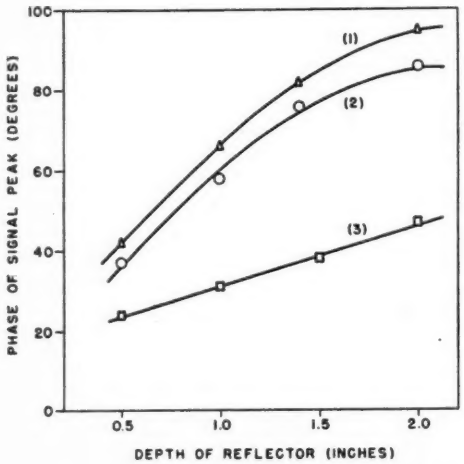

FIG. 12a. Comparison of Image and Reflected Signals, Non-Concentric Loops. Phase of First Peak of Signal as a function of Depth of Reflector. Loops 1 inch mean diameter, 5 inch center separation. 180° current pulse. Frequency 2.04 cps. Aluminum I "model." Curve 1—image signal; Curve 2—reflected signal from iron; Curve 3—reflected signal from air.

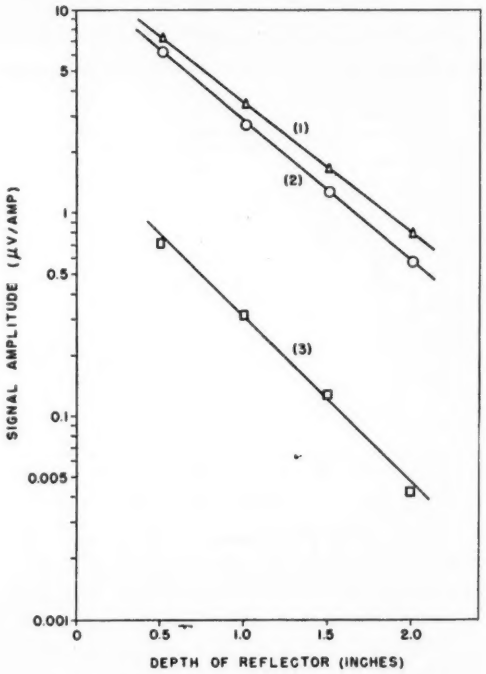

FIG. 12b. Comparison of Image and Reflected Signals, Non-Concentric Loops. Amplitude of First Peak of Signal as a function of Depth of Reflector. Same experimental arrangement as Figure 12a. Curve 1—image signal; Curve 2—reflected signal from iron; Curve 3—reflected signal from air.

VI. ILLUSTRATION OF MODEL USED FOR PROFILING AND COMPARISON OF MODEL AND FIELD RESULTS

A. *Illustration of Model Used for Profiling*

A localized highly resistive body embedded in the earth—similar to a salt dome—was modeled by cutting an oval shaped hole in a 2-inch thick aluminum plate and then placing it beneath several solid aluminum plates. The aluminum-air resistivity contrast was then detected as a reflected signal using a homogeneous "model" to cancel the boundary wave. Non-concentric loops of 1 inch mean diameter and 2.5 inches center separation and a pulsing frequency of 2.04 cps

were used. The depth from the surface to the top of the "salt dome" was 1.5 inches and the dimensions of the dome axes were 3 and 5 inches. In Figures 13a and 13b are shown profiles taken across the dome with two different orientations of the loops with respect to the axes of the dome. The edges of the dome can be readily determined from the first and second peak amplitude curves on both pro-

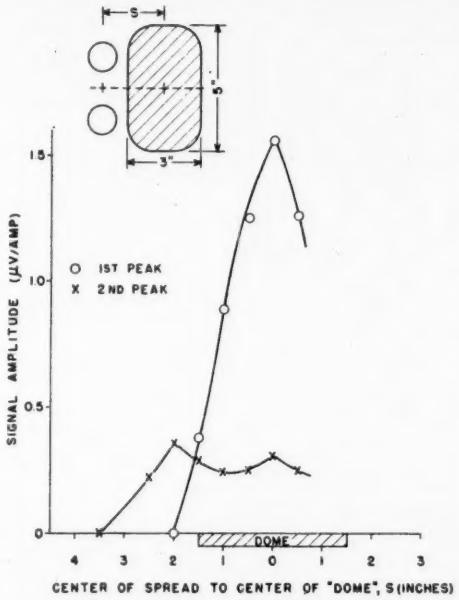

FIG. 13a. Profile Across Model of Salt Dome, Loop Spread Axis Parallel to Edge of Dome. Signal amplitude as a function of distance between center of dome and center of non-concentric loop spread. 1 inch mean diameter loops, 2.5 inches separation. 180° current pulse. Frequency 2.04 cps.

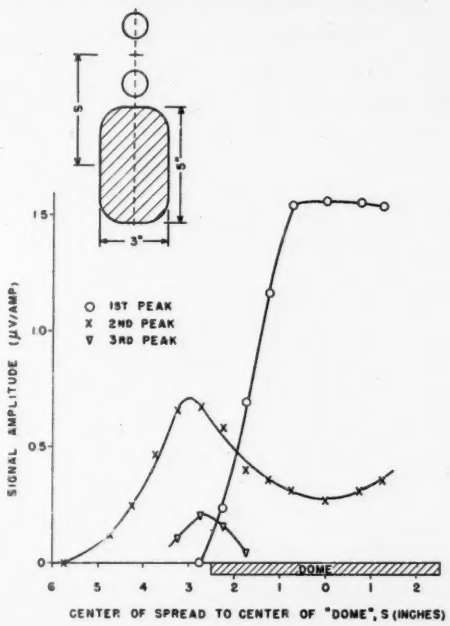

FIG. 13b. Profile Across Model of Salt Dome, Loop Spread Axis Perpendicular to Edge of Dome. Signal amplitude as a function of distance between center of dome and center of non-concentric loop spread. Same loops, pulse length and frequency as Figure 13a.

files. The maximum amplitude of the second peak occurs before both loops are over the edge of the dome (center of loop spread about $\frac{1}{2}$ inch from edge). The first peak appeared when the center of the loop spread was over the edge and increased in amplitude until both loops were well over the "dome." In the profile of Figure 13b a third peak in the reflected signal was observed and its maximum amplitude occurred with the loop spread directly over the dome edge.

B. *Comparison of Model and Field Results*

Field tests using non-concentric loops were made in an area in Oklahoma (Tillman County) where the earth conditions were essentially that of a single thick reflector 700 feet deep with a resistivity contrast of 275 to 1. The field data were taken with an instrumentation system that measured the total signal averaged over 20 degree intervals. The boundary wave that was subtracted from the

field signal to obtain the reflected signal was computed from dc resistivity measurements in the area and the theory given in Part I. In Figure 14 the complete shape of the reflected signal thus obtained is compared with the reflected signal from the model of the same earth conditions (model signals were averaged over 20 degrees before plotting data) where the boundary wave was automatically cancelled. The general agreement in phase and amplitude is the outstanding feature of these curves. The actual differences between the field and model curves are due in large part to the inaccuracy of the field data. Errors of 5μv/amp which are apparent constitute an appreciable percentage of the reflected signal amplitudes.

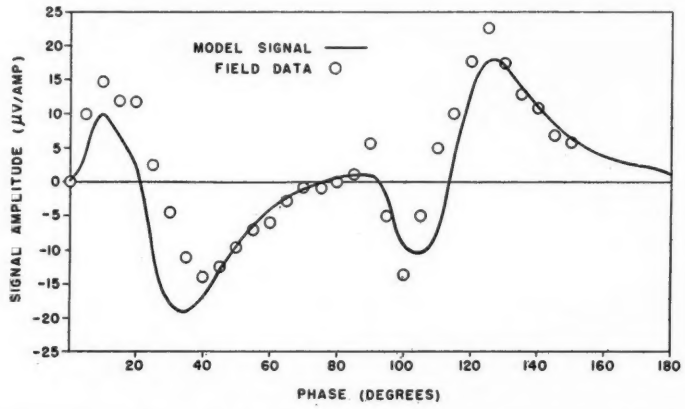

FIG. 14. Comparison of Model and Field Results, Reflected Signal from Single Reflector. Nonconcentric loops, 2,500 feet between centers on earth. Frequency 3.75 cps. 90° current pulse. o—field data; solid curve, model signal after averaging over 20° intervals.

ACKNOWLEDGMENTS

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LIMITATIONS OF THE SEISMIC METHOD OF MAPPING FAULTS*

FREDERICK ROMBERG†

ABSTRACT

The limitations inherent in the seismic method of mapping faults are listed and classified. These limitations are divided into instrumental, physical, and geological. An attempt is made to treat them quantitatively and to find places where the accuracy of the seismic method can, or cannot, be improved in the foreseeable future. Attention is called to the fundamental assumptions of seismic prospecting, the prevalence in practice of contradictions of these, the inability of present methods to do what is expected of them, and the difficulty of checking their results. The role of non-structural prospecting is considered, on the basic of specific failures in current methods. A general equation for dealing with horizontal velocity changes is suggested in an appendix.

INTRODUCTION

This study was originally prepared as a talk before the Dallas Geophysical Society in December, 1951. It is speculative and critical in nature, and offers no observations or theory beyond what is already well known. Its main purpose is to examine the limitations inherent in the seismograph method of fault mapping and to evaluate them quantitatively, especially in relation to current practice and current requirements. It attempts, in addition, to predict which of them can be extended and which not. It considers briefly the assumptions under which seismic mapping is done, and examines the extent of their validity and points out some contradictions in them. The extent to which non-structural prospecting has been, and ought to be, used in the search for faults is tentatively evaluated. Some remarks on the responsibility of geophysicists are offered.

The question immediately arises as to the value of such a theoretical study. Nearly all the problems it lists are, in the long run, soluble only by experimental evidence—evidence neither easy nor cheap to get, or it would have been available long ago. Indeed, it is the history of seismograph prospecting that, aside from instrument construction, theory has not been particularly helpful in advancing the art. It was once scientifically argued that it would be impossible to observe reflections. Even now, the theory a practitioner of the art of interpreting reflections must know in order to perform his daily tasks was all available in elementary college texts before reflection shooting had been invented. There is no demonstrable connection between the ability to find oil and a familiarity with the theory of elasticity. If this is so, then what is the use of pursuing an inquiry which is neither experimental nor mathematical, but only critical and speculative?

This question has two answers. The first one is that proper experimentation

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is so difficult and expensive that it is seldom done, and we simply make out the best we can without it. The consequence of this is that we tend to assume things about the relation between seismic data and geologic structure which we should be more careful about if we knew our guesses were to be tested by experiment. It is reminiscent of the early days of learning, before experimental tests came to be required in science, and there was much emphasis on the particular skill and virtuosity of individuals. The same thing can be seen today in psychology and economics, with their contradictory schools and dogmas. The universal and objective science of our day could not develop until individual performances and claims were ruled out in favor of standard methods of testing. Seismograph prospecting is no exception to this rule. The secret and conflicting methods of different interpreters are a deterrent to progress, just as they were in the days of alchemy; and the art of seismic prospecting can be expected to increase its effectiveness in proportion as it grows out of the old individual ways and develops into an engineering technique.

A suitable attack on this problem is of course not hard to suggest. The first step in reducing the finding of faults to a regular technique would be to examine all case histories available, separate the successes from the failures, and try to discover significant criteria for differentiating one from the other. But in practice it is not possible for anyone to study a suitable number of cases, and if it were these cases would still be selected from those which were initially favorable, and therefore tested. It follows that we are reduced to theory and logic rather than inductive methods for our general attack. One way to proceed might be to examine the logic of our methods to make certain that we do not in practice infer more than our data can possibly tell us, nor make unjustifiable claims for ourselves. It is something like making sure that we are not drawing conclusions from the third significant figure when we have data accurate only to two. This is a proper and productive use of logic, and yet it is usually done only casually in seismograph work.

Another good use for logic is in looking for contradictory assumptions. If there are contradictions in our methods, it is quite likely that we can improve our performance by resolving them. It may therefore be fruitful to set down explicitly the theory of seismic prospecting, in order to see whether we are justified in making the claims which we, in default of experimental checks, live by.

The second answer to the question of whether this study is worth while is an experimental one. Today, in the regular search for oil, we seismologists are asked questions by geologists which we can, as a matter of statistical fact, not answer. Everybody knows that, in areas important to oil production, it is common not only to miss a fault critical in the location of oil, but in addition to be able to discern no seismic evidence of it even after it has been found by the drill. Conversely, such faults are often mapped and then not found when sought by the drill. Yet these faults are the very crux of the search for oil in a large part of the world. What it amounts to is that we are not doing what we say we can do; it is clearly up to us either to modify our claims or else improve our performance.

It may be argued that the observations to be presented here lead merely to additional decimal point chasing in existing methods and are in consequence of little real value. In fact, it is possible to say that most oil fields that are being found in worked-over areas like the Gulf Coast are discovered through a combination of random good fortune and an optimistic drilling campaign in which wells are located on anomalies as such rather than on certain types of structure. A corollary of this viewpoint is that our structural maps are at least partly meaningless and that we ought to admit it and try to simplify, rather than to elaborate, such maps. This viewpoint is set forth by Rosaire[1,2] and has probably applied to more cases of "non-structural prospecting" than the average geophysicist admits. However, it is at present a fact that petroleum geologists, when they wish to locate wells, ask questions in terms of structure and criticize the results in the same way. If such terms are meaningless with respect to geophysical data then it is up to the geophysical profession to prove it so, with examples. This study is an attempt to consider how close the relation between geologic structure and geophysical data is, and where and how it can be made closer. In other words, how much difference is there between what we really do and what we think we do.

THE ASSUMPTIONS OF SEISMIC PROSPECTING

Before proceeding to study in a quantitative way the limitations of present methods of mapping seismic structure, it is proper to consider the basic assumptions under which such mapping is attempted. Laboratory measurements in today's scientific and engineering practice are carried on in certain well-understood ways and are tested by commonly accepted criteria. Geophysics, and particularly seismic prospecting, uses methods and instruments that are borrowed directly from laboratories but used in ways which are extrapolations from laboratory practice. It is a little like making astronomical observations; we assume the laws of physical optics hold, though we are actually unable to find out; so that we shall never really know what we are doing when we state the result of those observations. Seismic mapping is the same way. We state conclusions more variegated than any astronomer ever dared to, on assumptions much less logical than the laws of physical optics. What, then, are these assumptions, and what chance have they of being true enough to do us any good in finding oil?

The first assumption is of course that the boundaries and surfaces which give us our reflections have meaning with respect to petroleum prospecting. For the simpler cases this is clearly true—or at least so close to being true that it makes no difference. An anticline in the Georgetown, or the Rodessa fault, are plain examples. Almost at the other end of the scale is the piercement-type salt dome with a rim syncline, where very few reflections can be observed at all, and these have no particular relation to the places where oil may be found. And there are

[1] E. E. Rosaire, "Prospecting Effectiveness." *Geophysics*, VI, 4 (1941), 428–448.

[2] ——— "Studies in Non-Structural Petroleum Prospecting," *Geophysics*, XVI, 3 (1951), 456–467.

all states in between. In particular, in the case of a complicated and criss-crossed fault pattern, there is the dual uncertainty as to whether the small-scale tilted blocks that seem to confine the oil will furnish recognizable reflections, and whether, conversely, we can sort out the reflections we observe well enough to recognize these blocks. The stratigraphic trap and the reef are other important examples of marginal cases of our basic assumption. The assumption then is sometimes valid and sometimes not; and the seismologist is responsible for drawing the line.

The second assumption stems naturally from the first. We assume that reflecting surfaces are important; we also assume they can be recognized and understood. But this assumption, like the first one, is clearly valid in some cases and clearly false in others, and on each prospect the seismologist must judge whether he can or cannot proceed on it. The decision is apparently not simple. Quarles[3] has shown that reflections on the neighborhood of fault planes are subject to misinterpretation of various kinds; Rieber[4] offered the hypothesis that diffracted energy may be observed on records; Swartz and Lindsey[5] have described highly refracted reflections, and many authors[6] have discussed seismic events that are multiply reflected. It seems probable that much false interpretation is currently done through over-simplified ideas as to the origin and history of the wave fronts observed on seismograms. Better interpretation techniques will no doubt improve our understanding of reflections, but our instruments and the earth itself set fundamental limits to this understanding.

The third assumption is that reflections are correlatable from one trace to another and from one spread to another. Correlations fall into two classes: correlations from trace to trace by reason of proximity and time ties, and correlations from record to record based on interval and "character." The first type of correlation can be held valid if the dip does not change and the reflecting horizons are continuous enough physically to give continuous reflections. But when there is a break in the reflection sequence it may or may not be caused by a break in the reflecting surface. A change in the physical nature of the reflecting bed may have occurred, or a change in the filtering characteristics of the surface, or there may have been a fault, or—which is probably most common—the dip has changed. When the dip changes—that is, when what we are looking for happens—the relation of depth points to shot points is scrambled, so that, for example, a trace south of its neighbor may have a depth point north of that of its neighbor. When this happens, to map the depth points in a normal sequence is a contradiction and it is clearly up to the geophysicist to decide when such a contradiction is so serious as to invalidate his results.

[3] M. Quarles, Jr., "Fault Interpretation in Southwest Texas," *Geophysics*, XV, 3 (1950), 462–476.

[4] F. Rieber, "Visual Presentation of Elastic Wave Patterns under Various Structural Conditions," *Geophysics*, I, 2 (1936), 196–218.

[5] Swartz and Lindsey, "Reflected Refractions," *Geophysics*, VII, 1 (1942), 78–81.

[6] *Geophysics*, XIII, 1 (1948).

The other type of correlation, based on "character" and interval, poses a different problem. Where there has been a break in the reflecting bed, the only way to relate a reflection on one side of the break to one on the other is by character—that is, by the relative prominence of a burst of reflected energy coupled with a set of forerunners or followers arriving at such out-of-phase times as to give a consistent and therefore diagnostic change in the appearance of the main energy. But such a diagnostic appearance of character is an accident, easily destroyed or changed by small changes in frequency, and discouraged by over-filtering. A geophysicist who uses such similarities in seismic mapping is guessing—perhaps intelligently, perhaps not, but still guessing; he is practicing imaginative geology rather than scientific geophysics. This fact is important in any attempt to divide the functions of seismologist and geologist by drawing a sharp line between the collection of physical data and its geological interpertation. Blau[7] draws such a line as between men or professions, but the foregoing shows that this may not be desirable. It is arguable that the best results in geophysical prospecting may come from a more complete combination rather than a more careful division of the two functions.

The fourth assumption is that the seismic velocity field is known. This assumption is sometimes of little enough consequence that useful seismograph work can be carried on by assuming that the velocity is constant and its magnitude has no significance, as when cross-sections are plotted in time, with an arbitrary scale for the vertical dimension. But there are clearly cases where even an approximate knowledge of how the velocity changes with depth may be important, such as when it is desirable to measure the dip or the changes in relative thickness of formations. Finally, there are cases where velocity changes in a horizontal direction ought to be taken into account. These have been recognized in the literature but are so far not dealt with routinely in practice, though every seismologist has seen places where regional and local changes in the velocity are great enough to be critical in useful work. Stulken[8] shows examples where assuming that the velocity does not change horizontally leads to an error of 600 feet per mile in the depth. A false dip of this magnitude could easily disguise an oilfield. Rosaire[9] and Quarles[10] have shown that local changes in velocity occur around salt domes and faulted areas, but attempts to make computations taking this into account have not come to the attention of the author. Such attempts would no doubt be costly and marginal on account of the extreme difficulty of measuring local changes in seismic velocity, but they might some day be considered worthwhile as against the cost of dry holes. A suggestion for making such computations, provided a rate of change of velocity were assumed, is offered as an appen-

[7] L. W. Blau, "The Interpretation of Geophysical Data," *Geophysics*, II, 2 (1937) 95–106.

[8] E. J. Stulken, "Seismic Velocities in the Southeastern San Joaquim Valley of California," *Geophysics*, VI, 4 (1941) 327–355.

[9] E. E. Rosaire, "Shallow Stratigraphic Variations over Gulf Coast Structures," *Geophysics*, III, 2 (1938), 96.

[10] M. Quarles, Jr., *op. cit.*

dix to this paper. In any case, it is obvious that since velocity changes can be important in the seismic picture, the geophysicist must know that they exist and decide whether he can, or should, take them into account.

The fifth assumption is that the ordinary laws of refraction and reflection—that is, of geometric optics—are valid. It seems trite to dwell on this, and yet it is sometimes customary to ignore these laws, or at least to assume that they hold part of the time and not the rest. For instance, to assume that all reflections occur at a depth point (horizontally) halfway between shot and recording points, even if the beds from which they are reflected dip, is a contradiction. While the effect of such contradictions is not always serious, they cast doubt on the interpretation unless they are correctly evaluated at all times so as to see if it is safe to ignore them. Another place where contradictory assumptions are made is where the effect of velocity changes on the seismic path is ignored. This effect is usually less important than the effect of ignoring dip, but both have caused oilfields to be missed and dry holes to be drilled. One way to resolve this difficulty is for the geophysicist to plot only arrival times, which are the only data he can measure accurately, and let the geologist take the responsibility for what they mean. But the guessing and extrapolation necessary to get the most information out of such data ought to be done by the person who has the best understanding of how they are obtained; to wit, the geophysicist. If he leaves the final stage of interpretation to the geologist he is responsible by default for what happens.

THE LIMITATIONS OF PHYSICAL MEASUREMENTS

As an approach to the question of how well seismic mapping can actually be done, we may start by considering the limitations of measurement in general, and then see how these apply to our particular subject. It is a commonplace to the technical world that physical measurements are not absolute, and that each one has a limit of accuracy and precision beyond which the terms of measurement have no meaning. The classical example of this is, of course, the yardstick; the length of an object cannot be measured by a yardstick to plus or minus three thousandths of an inch because the yardstick's graduations are so coarse that their edges are uncertainly located in space, and because there is a parallax between them and anything that is set down beside the stick. The limits of physical measurements fall into two classes. The first is a limitation due to the measuring method, such as that imposed by the wave length of visible light in a microscope. The second is a limitation due to the object to be measured, such as the uncertainty caused by the indistinctness of a body's edge or end.

Both of these types of limitation are important in seismograph prospecting. The effect of the first type is, of course, obvious. The sound wave of a given wave length cannot be expected to resolve a structure smaller than that wave length. (This matter has been commented on by Clewell and Simon[11] but apparently there is no experimental evidence available on how thick or how wide a reflecting

[11] Clewell and Simon, "Seismic Wave Propagation," *Geophysics*, XV, 1 (1950) 50–60.

layer has to be before it can be recognized with the seismic waves used in oil prospecting.) Another limitation of the same type is that imposed by the ear which is being used to listen to the sound—that is, the seismometer spread. Considered as a receiving device for sound, the seismometer spread is subject to severe practical limitations in size and scope, on account of the necessity for economy and for selectivity in direction and frequency; these limitations will be dealt with particularly in the text to follow.

Limitations of the second type, that is, those imposed by the quality of the object to be measured, are plainly of extreme importance, since the whole performance hinges on our ability to get a sound wave of usable frequency, sufficient magnitude, and recognizable direction to be reflected from some surface which is diagnostic in the finding of oil. This is a large order and has so far been accomplished mainly by accident; no quantitative observations have been made on the characteristics a geological boundary must have before it can be perceived with sound waves of the kind we use.

Johnson[12] and Robinson[13] have published cross-sections on which reflections appear to have come from fault planes, for example, but how often and under what conditions this occurs is apparently quite obscure.

SPECIFIC LIMITS IN FAULT INTERPRETATION

It is now appropriate to try to list more specifically and quantitatively the factors which at present set limits to the precision of seismic interpretation, especially with respect to fault pictures. In some matters we may be fairly quantitative; if the answer given is wrong its probable error may at least be approximated. In others it may forever be impossible to improve things, or even evaluate the uncertainties, so that the usefulness of present-day seismic work may be considered to have reached a natural limit, at least in the present relation of geophysical costs versus drilling costs versus the price of oil.

A. *Instrumental Power:*

First, and easiest to evaluate, in the list of specific limitations are those due to the instruments themselves. These comprise the precision and resolving power of the apparatus, the mistakes due to its inappropriate use, and its inability to record usable reflections.

The limits of accuracy of the instruments are fairly easily evaluated. If one assumes a maximum error of $\frac{1}{2}$ millisecond in the time break, one millisecond in the reading of the weathering break, and 3/2 milliseconds in the arrival time of the reflections, this permits a possible error of 7 milliseconds in relative arrival times of two correlated reflections. In a typical case this corresponds to an error

[12] C. H. Johnson, "Locating and Detailing Fault Formation by Means of the Geo-sonograph," *Geophysics*, III, 3 (1938), 273–291.

[13] W. B. Robinson, "Refraction Waves Reflected from a Fault Zone," *Geophysics*, X, 4 (1945), 535–545.

in the relative depth of 35 feet. This is, of course, larger than the probable error; but on the other hand the magnitudes given are quite conservative, especially in the arrival times of reflections, since these are interfered with by irrelevant ground motion and frequency change. In general, then, a measured depth difference of 30 feet, determined from only one pair of records, is within the limits of error of the apparatus, and therefore meaningless or at least marginal in mapping structure. Depths computed from an average of several records are of course more accurate; quadrupling the number of records halves the error. There seems little hope of reducing the error substantially by any other means, since its largest component comes from the reflection arrival time, and as long as present-day frequencies are used these times will probably not be more precisely readable than they are now. There has certainly been little reduction of the reading error since 1934.[14]

It seems quite likely that both instrumental precision and resolving power would be improved if high-frequency sound waves were used. Experiments[15,16] have been made in an attempt to transmit through the earth shorter waves than are now in standard use, but their application to seismic work seems to depend on the development of an acoustic source more powerful than the ones now available, and it is hard to foresee improvement to the art in this direction.[17]

An attempt was made by Rieber[18] to improve the directional resolving power of the seismograph by a sort of electrical scanning of the traces of a record for reflections arriving in different directions. Apart from the claims made for this method, the attacks it sustained and the small amount of actual testing it got, there is undoubtedly merit in the idea. It is obvious that an objective, automatic method of measuring the degree to which traces on a seismograph record line up and resemble each other would be an improvement over the eye-and-pencil method now used, for the sake of consistency if not economy. It would surely be possible to invent modifications of the Rieber "sonograph" which would take into account all the *objectively existing* characteristics of events on seismograms more accurately and cheaply than the currently existing staffs of computers and seismologists can do it. The Rieber method had the additional advantage of two-stage recording so that the original record could be re-run with different filters in the office.

The mistakes due to improper use of the apparatus might be listed as miscorrelations, invalid weathering corrections, and failure to measure wave front

[14] F. Goldstone, "Mapping of Geologic Structure by the Reflexion of Elastic Waves," *Trans. Soc. Pet. Geoph.*, V (1935), 132–153.

[15] Howell, Kean and Thompson, "Propagation of Elastic Waves in the Earth," *Geophysics*, V, 1 (1940), 1.

[16] F. F. Evison, "An Electromechanical Source of Elastic Waves in the Ground," *Proc. Phys. Soc.*, 64 (1950), 311–322.

[17] Clewell and Simon, *op. cit.*

[18] F. Rieber, "Complex Reflection Patterns and their Geologic Sources," *Geophysics*, II, 2 (1937), 132–160.

direction (dip). Miscorrelation will be discussed further under *Geologic Limitations*. Weathering corrections can usually be brought within the limits of error of the apparatus by individual treatment, either by modifying the spread or just by more careful computation. Failure to measure wave front direction can be dealt with by shooting a cross-spread of some sort, but taking dip information fully into account in interpretation is more difficult. To date, there exists no method for complete three-dimensional study of seismic information which is not too cumbersome for everyday use, though the ordinary subsurface map, with its fault blocks tilted in all directions, makes the need for such a method obvious. This is one of the frontiers of practical geophysics; an indeterminate improvement in daily work would surely result if a good way to treat three-dimensional data thoroughly were invented. It is the author's opinion that the art has lagged farther behind the potentialities of available technique in this matter than anywhere else in the industry.

A third class of limits set by geophysical instruments consists of those due to practical requirements for getting reflections—spread, filtering, weight and dimensions, and so on. Reflections can be improved in appearance by reducing the size of the spread, but at the expense of accuracy of dip as well as economy, and the grouping used to reduce noise also reduces efficiency in receiving oblique wave fronts. The instrumental set-up is of course always subject to development in convenience and economy, but this affects only indirectly the main object, which is to get records that can be more correctly interpreted. Present-day methods of filtering and volume control, for instance, are in the main adequate for accomplishing anything the seismologist specifies; but the optimum specifications are still unknown. The incoming energy must be filtered to be intelligible, but the more filtering the less fidelity. The possibilities of correlation by "character" may be largely vitiated by over-filtering; this is a place where research with available techniques might be rewarding. The same things can be said of volume control. It is probable that the optimum points in both volume control and filtering are different for different locations, and therefore also probable that they have been reached and passed by the different circuits now in use. The consequence is that over-all improvement will not depend on new discovery or invention but on the development of more versatile instruments multiplied by the use of better judgment by operators. It is likely that the demands of the industry will stimulate some progress here, though revolutionary change appears improbable.

B. *Physical Limitations:*

More important than the limitations imposed on seismology by geophysical techniques are those due to the nature of the earth. These natural limitations can be divided, somewhat arbitrarily, into two classes: geological and physical. The geologic limitations are those imposed by the structural and stratigraphic features about which the geologist seeks information; the physical ones are those

imposed by conditions in the ground through which the seismic waves must travel. The physical limitations can be classified as those due to near-surface conditions, to broken reflecting surfaces, to disturbed zones at depth, and to velocity anomalies.

The near-surface conditions comprise the well known filtering effects of shot holes and set-ups. Techniques for improving the records by varying the positions of shot and seismometer, including burying the seismometers, have been studied since the beginning of seismograph work, but at present these techniques seem pointed rather at getting good records in poor places than at producing any revolutionary improvement. Pattern shooting and recording offer some promise in this direction, but in general do not now seem to offset their extra cost.

Broken reflecting surfaces and disturbed zones through which reflections must pass set even more fundamental limitations to seismic work than unfavorable surface conditions. It looks as though the only way to deal with them effectively would be to recognize criteria for their presence and avoid them, though it has been pointed out that if they can be recognizeed their presence may be diagnostic of something.

Velocity anomalies, especially local ones, pose an extremely discouraging problem because, as previously mentioned, they are so difficult to find and to measure. As of now, local velocity anomalies cannot be dealt with except by remembering that they may be present, and enlarging the expectation of error accordingly. It is possible that in the future typical magnitudes for these, in places like the neighborhood of salt domes and other disturbed areas, may be measured so that they may be taken into account approximately, but nothing to encourage this possibility has been published so far. Indeed, the data given by Quarles[19] seem to show that the existence of velocity changes in the neighborhood of fault planes is irregular and unpredictable. It follows that unless his interpretations are found to be untypical or are brought into some sort of regularity there seems little hope of progress in analyzing multiply faulted areas. In the writer's opinion the next step in developing seismic technique is to find valid criteria for knowing when detail in fault interpretation is no longer reliable.

In sum, then, the limitations set by physical conditions represent to the seismograph prospector mountains to be skirted rather than scaled. The line of behavior indicated seems to be an understanding and avoidance of the difficulties rather than a solution of them. It is to be hoped that this analysis of the situation is wrong, but if it is not the seismologist will shortly find himself considering nonstructural prospecting instead of refining the structural prospecting techniques he now uses.

C. *Geologic Limitations:*

The limitations imposed by geologic structure on seismic mapping are probably the ones least understood in the industry and, therefore, those most likely

[19] M. Quarles, Jr., *op. cit.*

to be affected by theoretical study. In general the data used in mapping faults tend to be computed and plotted under assumptions which are supposed to be simplifications but which may turn out to be self-contradictory. One of the main purposes of this paper is to point out certain places where self-contradictory assumptions are used in general practice and to call attention to the handicap this puts on correct interpretation.

The following geological configurations will be mentioned:

1. Faults with small throw.
2. Dips and curved surfaces which result in displaced depth points.
3. Complicated fault patterns.
4. Cancellation and interference between reflections.
5. Discontinuous reflecting surfaces.

The throw of faults is of course one of the principal elements in determining whether they can be mapped by seismic methods. The occurrence of faults with a small throw is important in the accumulation of oil. But if this throw is less than the relative error to be expected between two seismic depth determinations then its existence on a seismic map is questionable. In a simple case a remedy for this is the quantitative one; if, by increasing the number of relevant determinations the expected error can be reduced well below the assumed throw of the fault, then it is reasonable to map the fault. If not, the interpreter is deceiving himself when he puts such a fault on the map. It is important to observe that much uncertainty exists in small faults mapped by other means, so that if it is carried too far the whole question is meaningless in geology as well as geophysics. It clearly behooves practitioners of both arts to know where this border-line of physical meaning lies; and in practice this will be better accomplished by close-knit cooperation instead of rigorous separation of the two professions.

The displacement of depth points with respect to shot and recording positions poses a more complicated problem, and it is here that geometric analysis of the plotting method may improve the results significantly. It is clear, for example, that reflections from either side of a sharp syncline may cross each other in the earth, so that the reflection from the north side of the syncline is recorded south of the one from the south side. (See Fig. 1.) This makes it appear from the dips on the record that there is an anticline instead of a syncline, unless the horizontal displacement of the depth points is correctly evaluated. If the syncline is wide enough so that one reflection is observed from its center the commonly used method of continuous correlation may lead to a mis-correlation of a cycle, resulting in an attractive structure for drilling. The possible consequences to an oil company are obvious. Similar errors may easily result from failure to locate correctly the dipping beds associated with faulting, even in the absence of velocity anomalies and other non-geometric disturbances.

The same phenomenon, in an intensified way, must occur whenever the reflecting surface curves. A geological boundary which is convex will, of course, reflect rays originating from widely separated points on the surface, while one

which is concave upward will reflect only rays which originate from an area smaller than itself on the surface. If the concave surface, however, is deeper than its radius of curvature the rays will be inverted, as in the example of the sharp syncline above, and if it is deeper than twice its radius of curvature it will reflect rays originating over an area on the surface larger than itself and give a magnified and inverted "image." Since nearly all interesting geological boundaries are so because they do not have uniform dip; i.e., because they are curved surfaces rather than planes; the assumption customary in seismograph work that all re-

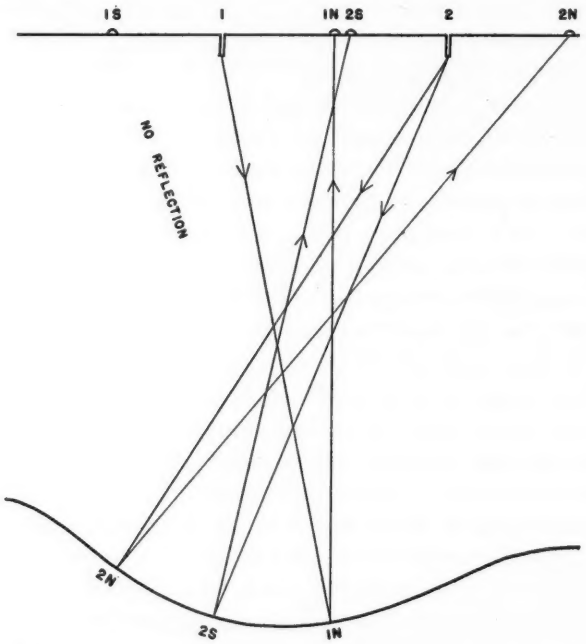

FIG. 1. Scrambling of depth points due to a syncline. Note that there is no reflection at IS.

flecting surfaces are planes is a contradiction. It is true that curved surfaces may be approximately treated by assuming that they are made up of small planes, but this assumption can be made only if the whole surface is large compared to the planes, and in today's seismograph work this is not generally true. In ordinary language, the dips and the changes in dips not only cause the depth points to "migrate" and scramble seriously, but also cause change in size and even direction of the sub-surface coverage and vitiate the assumption made in continuous profiling that the depth points of neighboring traces stand in the same relation to each other as their shot and recording points. An additional possibility for confusion arises from the fact that seismic energy may be concentrated in some places and dispersed in others so that reflections may be strong over synclines

and weak over anticlines. This notion is a part of the average computer's folklore.

These focusing effects were mentioned by Savit[20] but have not been properly dealt with in the literature. How well they could be taken into account by considering the laws of physical optics and by more careful computations generally is problematical. In the opinion of the author, much could be accomplished by recomputing and replotting cross-sections as successive approximations, taking the displacements and curvatures as developed successively into account. At any rate, it should be possible to criticize today's standard first-approximation cross-section as plotted on the ordinary seismograph party by considering whether the formations as plotted could possibly have given rise to the reflections used in plotting them.

When structures become complicated, with fault blocks smaller in horizontal dimensions than the distances between the shot points or the sub-surface coverage, the above-mentioned effects naturally make the whole picture harder to untangle. The difficulties caused by radial fault patterns, faults whose throw changes with depth, and faults intersecting in a vertical plane so as to make a graben at one level and a horst at another, can easily be imagined by drawing up examples from typical sub-surface maps of drilled-up structures. These complicated structures can be dealt with up to a certain point by reducing the spread and letting the lines as well as the shot points be closer together, but there is probably a practical lower limit to the useful size of a seismograph spread. It is possible that the future way to unravel complicated pictures might be to shoot an area, formulate a hypothesis as to the faults and dips in it, and then re-shoot with lines so oriented that the various fault blocks as postulated should give clear reflections. It might require several successive shooting patterns made to order before one of them would give the results predicted for it. Such a scheme would be no more expensive to the industry in the long run than the random re-shooting which is now done by different companies and therefore largely without the advantage of previous work, and if it were successful it might possibly accomplish that which has, so far, been considered impossible—a check on results without a drilling campaign.

A final type of geologic configuration which needs to be taken into account is the kind which produces interference or cancellation. If reflections arrive from different directions, such as from opposite sides of a syncline, they may be out of phase at one end of a record and in phase at the other; this will certainly look as though a strong reflection had suddenly given out and would be mapped by the average seismologist as a fault. In some cases it would be possible to clear the situation up by shooting with different filters or, what is the same thing, shooting at different depths in the hole. A further contribution might be made by shooting

[20] C. H. Savit, "Reflected Energy Variations Resulting from Small Changes in Shot Hole and Spread Locations," *Geophysics*, XV, 2 (1950), 219–226.

with the spread in a different direction, or somewhat off-set—in other words, to vary the geometric set-up so as to check a hypothesis, just as was suggested in the previous paragraph. It is plain that the phenomena of cancellation and interference may arise whenever the arriving wave fronts are not concentric—which means whenever there are any geological features of any interest—so that it probably occurs much more often than we realize.

CONCLUSIONS

A. *Assumptions*

We may summarize our observations about the assumptions under which seismologists work by saying that these assumptions hold in the simpler cases and become invalid in the more complicated ones. It is the duty of oil prospectors, whether they classify themselves as geologists or geophysicists, to understand the boundary or rather the border-land between where the assumptions hold and where they do not, as it is in that area that most prospecting is done. One of the consequences of this fact is that a sharp distinction cannot be made between the functions of the geologist and those of the geophysicist. Each has an essential contribution to make in rational and efficient oil finding, especially since a rule for discovering the next oil field can no more be set up than a rule for fighting the next war.

B. *Areas Where Little Progress is Foreseeable*

We have observed that the problems of instrumental precision, irregularities in the earth, and complicated and small-scale configurations, offer little promise for fundamental solution. The precision with which it is possible to make seismic measurements is limited by the nature of the earth rather than by our skill in constructing instruments. The impediments to measurement due to anomalous conditions in the earth can probably never be removed but must be recognized for what they are and circumvented by practical skill and intelligence rather than attacked by frontal assault. Lastly, the geologic configurations that are too small in scale, or too complicated, to be measured by our instruments ought not to be sought in detail beyond our rationally measured resolving power.

C. *Promising Areas for Research*

The areas where research offers promise for improvement may be divided into a practical and a fundamental class. Practical improvements may be made in the instrumental set-up by introducing two-stage recording, so as to make better filter control possible, and by automatic scanning for reflections, so as to make interpretation more objective. Computing and interpretation can be improved by getting—and plotting—data in three dimensions, and by closer attention to optical laws. Improvements in fundamental understanding can be made through basic study of the amount and quality of filtering which is optimum for the problem, through re-interpretation and possibly re-shooting until a self-con-

sistent and checkable picture is found, and above all through recognition of the inherent limitations of the apparatus and method.

D. *Responsibility for the Future*

Geophysicists will of course make their own future and that of the profession according to how well they adapt themselves to the problems now being set them by the oil industry and by society at large. Three of the main responsibilities they should assume are as follows: First, they should continuously balance the cost versus the utility of their work, in day-to-day prospecting as well as in research. Second, they should try to make their methods objective, and introduce engineering standards of measurability and consistency into the processes they carry out. Third, they should strive to approach their functions rationally so as to detect the limits of their apparatus and their assumptions, and to distinguish between structural and non-structural prospecting; in short, to know what they are doing.

ACKNOWLEDGMENTS

As the list of references show, the author is indebted to a wide cross section of the geophysical profession for the observations here collected. L. W. Blau, of Humble Oil & Refining Company, E. E. Rosaire, of Subterrex, M. W. Quarles, of United, and G. J. Long and Julian Pauley, of Standard of Texas, to mention the principal ones, contributed to the final result through discussions and conversations.

APPENDIX

In seismic prospecting the dips of reflections are usually computed, under the assumption that the velocity varies only vertically, according to the well known equation:[21]

$$\sin \theta = v\Delta t/\Delta x$$

where θ = angle of dip.

v = seismic velocity at the reflection point.

Δt = difference in arrival time across a "split dip" record.

Δx = distance between the ends of a recording set-up.

A more general equation, taking velocity gradients into account and therefore applicable where the velocity varies horizontally, can be derived as follows:

Let P_1 and P_2 be the mid-point (points halfway between shot and recording points) of two seismograph set-ups, or of two ends of a single set-up, shot in the direction of maximum dip.

Let Δx be the distance between P_1 and P_2.

Let t_1 and t_2 be the one-way travel times of a correlated pair of reflections from the two set-ups, corrected to a zero spread,

[21] M. M. Slotnik, "On Seismic Computations, with Applications, I," *Geophysics*, I, 1 (1936), 9–22.

Let DP_1 and DP_2 be the depth or reflecting points of the two reflections, and let r_1 and r_2 be the seismic path lengths between P_1 and DP_1, and P_2 and DP_2,

Let v_1 and v_2 be the average velocities between P_1 and DP_1, and P_2 and DP_2,

Let θ be the dip of the reflecting surface, which is assumed to be a plane.

We now have, in the approximation usually made,

$$\sin\theta = (r_2 - r_1)/\Delta x = (v_2 t_2 - v_1 t_1)/\Delta x$$

This becomes, if

$$(v_1 + v_2)/2 = V, \qquad (t_1 + t_2)/2 = T$$

$$v_2 - v_1 = \Delta V, \quad \text{and} \quad t_2 - t_1 = \Delta T,$$

$$\sin\theta = (V\Delta T + T\Delta V)/\Delta x$$

which is an interesting form of dip equation and may prove useful if there are horizontal changes in velocity.

THE SIGNIFICANCE OF DIFFRACTION IN THE INVESTIGATION OF FAULTS*

THEODOR KREY†

ABSTRACT

Seismic reflection records taken across faults frequently show an overlapping of reflections from the displaced blocks. It is demonstrated that diffraction of seismic waves is a cause and the effect may be used in interpretation. Overlapping is increased if a seismic profile crosses a fault at an acute angle. Plotted dips will be inaccurate unless diffraction is taken into account. Further, the diffraction oscillation pattern will also be obtained if a reflection horizon terminates for a reason other than faulting, for example, at a wedgeout or reef edge, or at a sudden change of facies. The facts developed are demonstrated by practical examples in which attention is directed to the approximations involved in plotting the boundaries of discontinuities.

In studying seismic reflection records taken across faults an overlapping of the reflections from the two displaced blocks is frequently observed (Fig. 1). Such an arrangement would be natural in the case of thrust faulting. But it will also occur where normal faulting is well known owing to geological reasons. In certain cases such an overlapping on seismic records may result from differences in dip on both sides of the fault. In the case of Figure 2, for instance, reflections would be obtained according to the laws of geometric optics by the seismographs placed on the right side of the shot point from parts of the horizon denoted by a as well as of a'(1). But since the said overlapping happens so frequently the aforementioned possibility of explanation cannot easily be accepted to hold good for all cases. The author, therefore, has put the question of whether the diffraction of seismic waves may successfully be used in their interpretation.

For this purpose calculations were made in order to find out what the oscillation pattern of a wave train of a frequency of 50 cycles and of $1\frac{1}{2}$ wavelength's time, with its integral being zero, would look like if the reflection takes place on a plane surface the termination of which lies directly below the shot point. The spread of seismographs should be at a right angle to the fault. The explicit formula of the described wave train would be:

$$f(t) = -\cos\frac{2\pi t}{50} - 0.212 \quad \text{for} \quad -\frac{3}{100} \leqq t \leqq +\frac{3}{200} \qquad (1)$$
$$\text{and } f(t) = 0 \text{ otherwise.}$$

This assumption is the most obvious one according to (2).

In Figures 3a, 3b, and 3c the effect as resulting from diffraction in depths of 2.000 m, 1,000 m and 500 m has been taken into consideration with a constant

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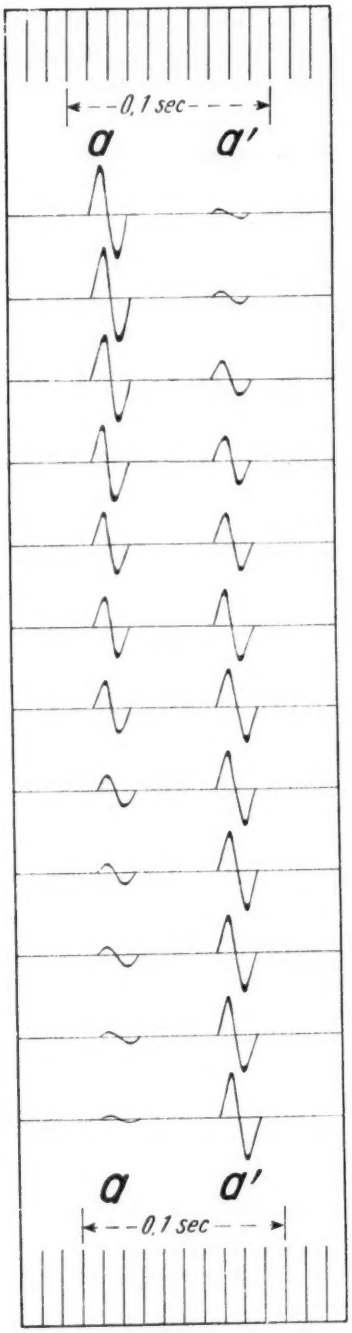

FIG. 1

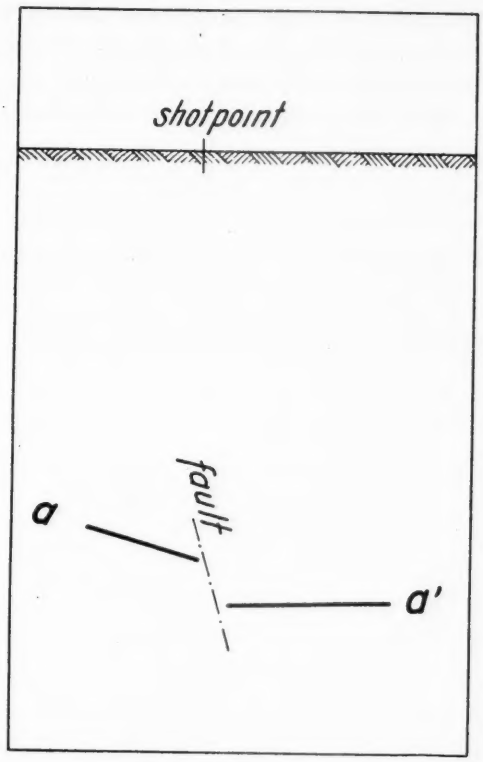

FIG. 2

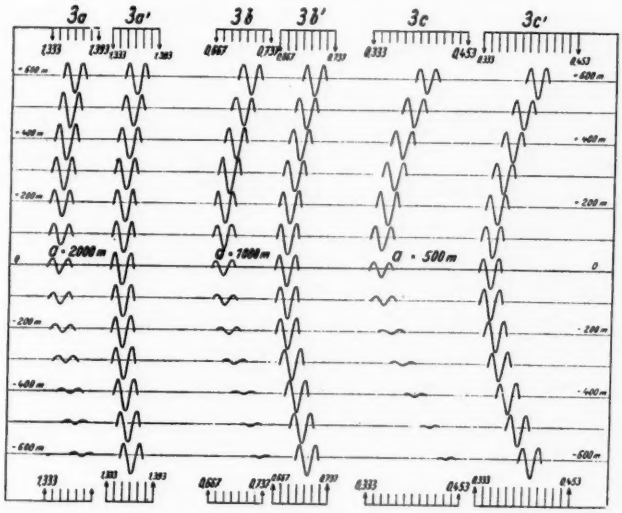

FIG. 3

velocity of wave propagation of 3,000 meters per second. From this, a wave length of 60 m will result. For the sake of simplicity, the construction of these figures was carried out in such a way that the beginning of the wave train was determined from the travel time on the geometrically shortest wave path and

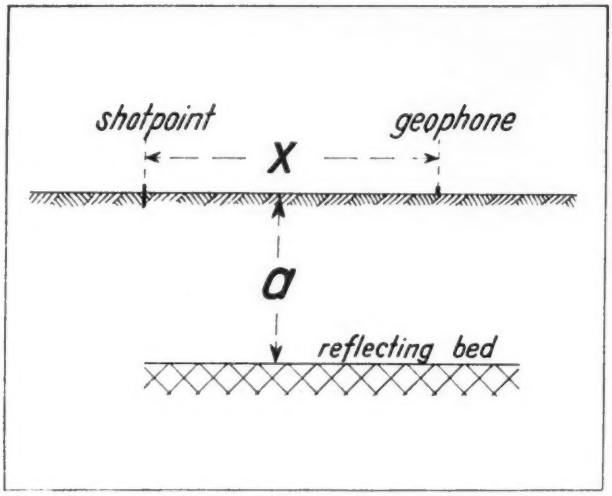

FIG. 4

that, as for amplitude and phase in the further course of the wave train, such data were used which resulted from continuous radiation according to Huygen's principle.

Let a denote the depth of the reflecting plane, x the distance of the geophone from the shot point counted positive above the reflecting plane (Fig. 4), t the travel time and λ the wave length, then, writing in the usual way

$$w = \frac{2\pi \cdot 3{,}000}{\lambda} \quad \text{and} \quad k = \frac{2\pi}{\lambda},$$

we obtain—setting aside a constant factor—for the elongation $v(x, t)$:

$$v = v_0 \frac{1 - i}{2} \left[F(w_2) - F(-\infty)\right] \cdot e^{-iwt}, \tag{2}$$

where

$$v_0 = \frac{e^{ik\sqrt{4a^2 - x^2}}}{\sqrt{4a^2 - x^2}},$$

and

$$w_2 = -\frac{1}{\sqrt{1 + \frac{x^2}{4a^2}}} \cdot \frac{x}{\sqrt{2 \cdot a}} \cdot$$

Herein

$$F(w) = \int_0^w e^{i\frac{\pi}{2}\tau^2} \cdot d\tau$$

denotes the so-called Fresnel's Integral (Cornus' Spiral). The derivation of (2) itself is already contained implicitly in ([3]), page 245, formulas 7 and 7a, and pages 250 to 252 (diffraction on a semi-plane) if, as shall be done here, the reflection coefficient is kept constant. The radiation has only to be considered as originating at the image point and the reflecting plane must be considered as a pervious semi-plane, whereas the block shifted by faulting must be taken as an impervious plane. Then for the values contained in formula 7, page 24 ([3]) we may write $R = R' = a$.

Of course, the above described way of representing the effect of diffraction is objectionable as we are not dealing with a continuous radiation in (1) but only

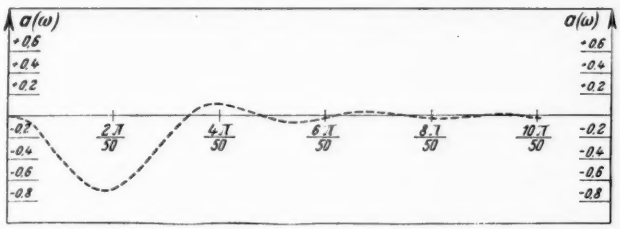

FIG. 5

with a short wave train. Strictly, the function $f(t)$ should be expressed by Fourier's Integral:

$$f(t) = \int_0^\infty a(w) \cdot \cos(w \cdot t) dw \tag{3}$$

Then, the effect of diffraction should have to be computed for each w and each x. Finally, the true pattern of oscillation would be obtained by integration over all values of w.

The calculation of the function $a(w)$ is relatively simple. It is represented in Figure 5.

To get an idea on the error involved in the incorrect diffraction computing procedure as given by Figures 3a to 3c, the author has calculated the above described exact path for $a = 2{,}000$ m and $x = \pm 600$ m, ± 400 m, ± 200 m and 0 m. The integral in formula X (3) was, however, replaced by a sum of four terms as follows:

$$f(t) \sim -0.39 \cos\frac{\pi \cdot t}{50} - 0.64 \cos\frac{2\pi \cdot t}{50} - 0.22 \cos\frac{3\pi \cdot t}{50} + 0.08 \cos\frac{4\pi \cdot t}{50}. \tag{3a}$$

The result has been given on a rather large scale by Figure 6. In this figure the

incorrect pattern of diffraction as drawn in Figure 3a has also been added for comparison indicated by dots and dashes. As may be observed, the deviations are not very important and do not essentially affect the considerations laid down in this paper. The differences appear to increase with larger distances—see, e.g., the curves for $x = \pm 600$ m. Attention has, however, to be called to the fact that the replacement of the integral (3) by the sum in (3a) is only a relatively rough

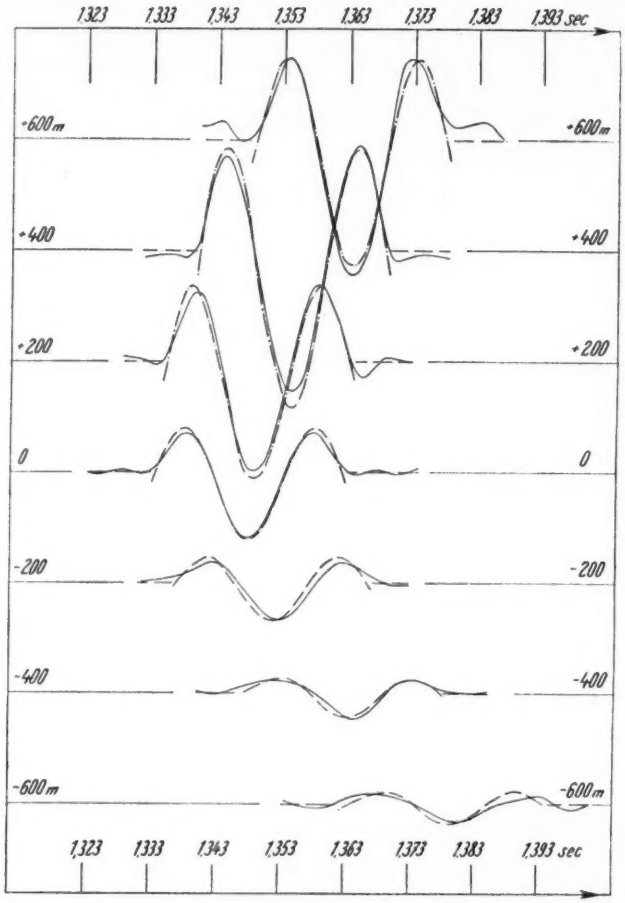

FIG. 6

approximation. The deviations resulting from Figure 6, therefore, are not to be considered quantitatively correct, but one should say that they give a good idea on the magnitude of the true error involved in Figures 3a to 3c.

The study of Figures 3a to 3c together with Figures 3a′ to 3c′, the latter representing the reflection pattern of the undisturbed plane will teach us two different things.

First: It is not possible to locate accurately the fault line since, according to

the magnitude of the noise level, the termination of the reflecting plane actually lying exactly below the shot point will be guessed either too early or too late. If X denotes the last distance at which the reflection concerned be recognizable the termination of the reflecting horizon would usually, without taking into consideration the effect of diffraction, be assumed at the distance $\frac{1}{2}X$. It may now be assumed that, if the signal-to-noise ratio is equal to 1, a point has been reached where a reflection is generally just no more recognizable. If, now, this ratio becomes 1.1 for an undisturbed reflection—this would mean that such a reflection is just recognizable—the termination of the reflecting plane, defined by the value of $\frac{1}{2}X$, would have to be assumed at about +100 m in the case of Figure 3a, about +70 m in the case of Figure 3b, and about +50 m in the case of Figure 3c. If the signal-to-noise ratio amounts to 3, i.e., we are dealing with a good reflection, the distance up to the termination of the reflecting plane would be about −70 m, about −50 m or about −35 m, respectively. If the aforesaid ratio is 6, i.e., we are dealing with a very good reflection, even values of about −250 m, about −175 m, and about −125 m would result.

It is, therefore, now quite easy to understand that overlappings as plotted in Figure 1 may occur. Further, from the foregoing analysis, deductions can be made as to the limits in exact determinations of faults. With respect to the boundary of the reflecting plane certain indications, however, result from the character of decrease in amplitudes. It can be shown, for instance, that the fault begins where the reflection amplitude is equal to half of the normal amplitude. But with the superposition of distorted waves and with the modern technique of full-automatic gain control it should be extremely difficult to recognize the true magnitude of reflected impulses.

Second: Now let us consider a very good reflection which according to the foregoing analysis is recognizable far across the fault up to great negative distances. Then, a notable slope in the direction of negative distances results from the time displacements occurring in Figures 3a to 3c if the reflection would be plotted as a single element. Figure 7 represents the elements resulting from the case given in Figures 3a to 3c. In the case of Figure 3a the evaluations for distances from −600 to +600 m on the one hand and from −600 to 0 m on the other hand are denoted by α or β, respectively. Accordingly, the evaluations resulting from the case of Figure 3b are denoted by α' or β', respectively, but instead of ±600 m they are based on ±400 m. Finally, in the case of Figure 3c α'' and β'' apply to even shorter distances of only ±300 m. The respective points of reflection formally resulting from the ray reflected in itself (sounding points) have been marked by short cross-lines.

In the opinion of the author the above described appearance of transition to sloping can be utilized to determine the position of a fault under favorable conditions as, according to previous discussions, the reflection amplitude itself is often only an insufficient expedient.

In addition, it must be mentioned that all considerations made so far will

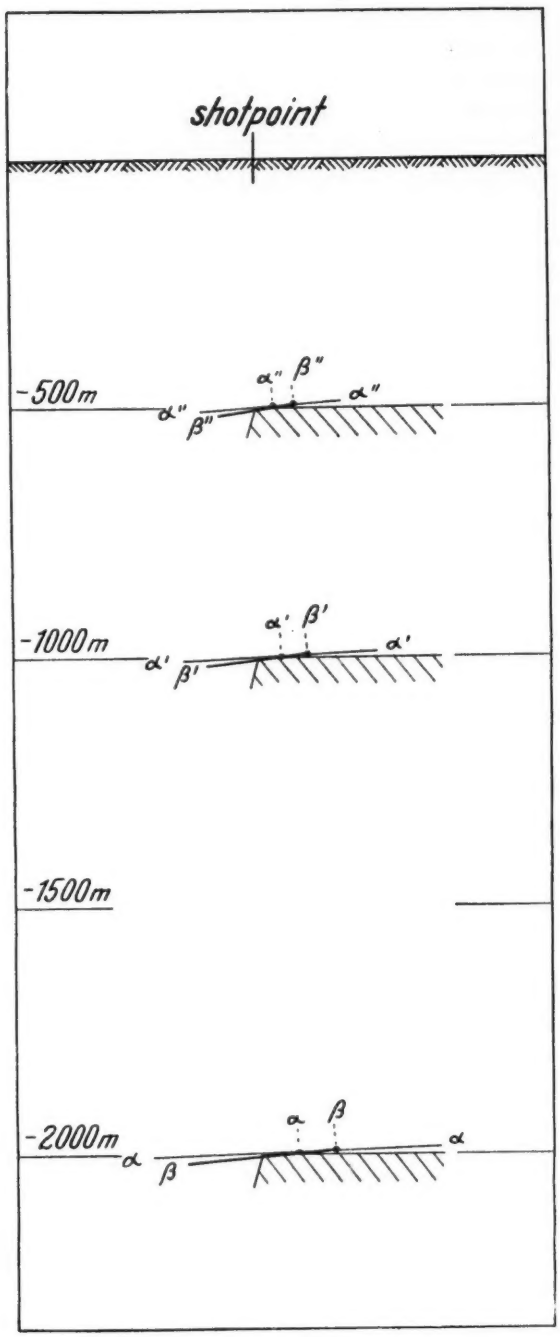

FIG. 7

similarily be applicable to faults not lying vertically below the shot point.

Figure 8 shows a fault located from reflections. The records of the left part of the horizon in front of the fault and marked *b* are represented in Figure 9. De-

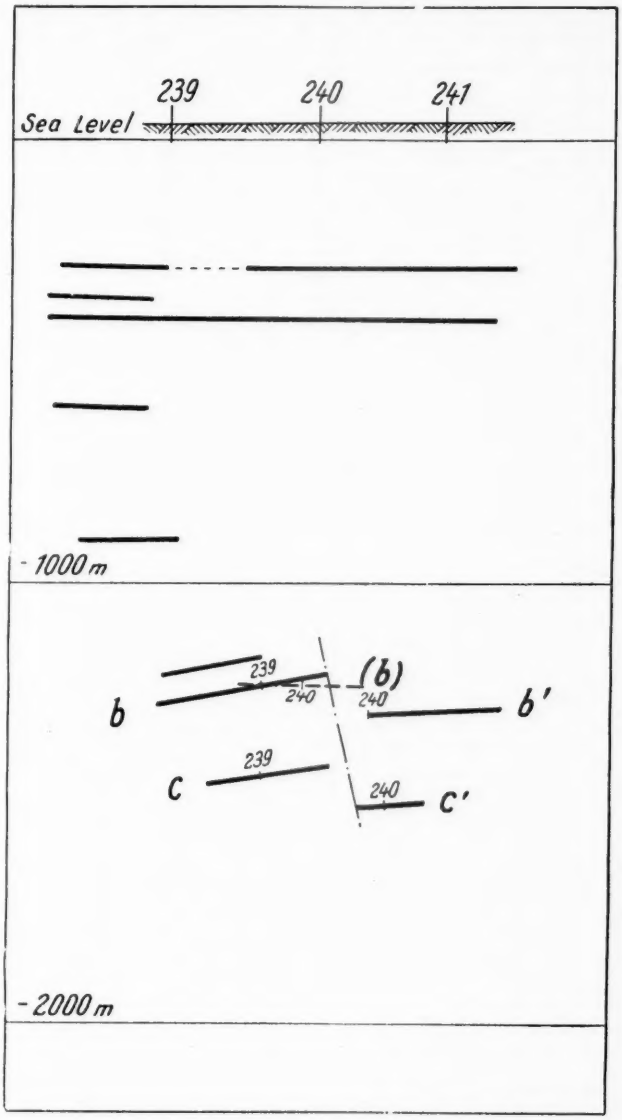

FIG. 8

crease in amplitude and transition to sloping is to be noticed on the lower half. The reflection of this part of the record has been plotted as a single element in Figure 8 and has been denoted by (*b*). The similarity with Figure 7 is evident.

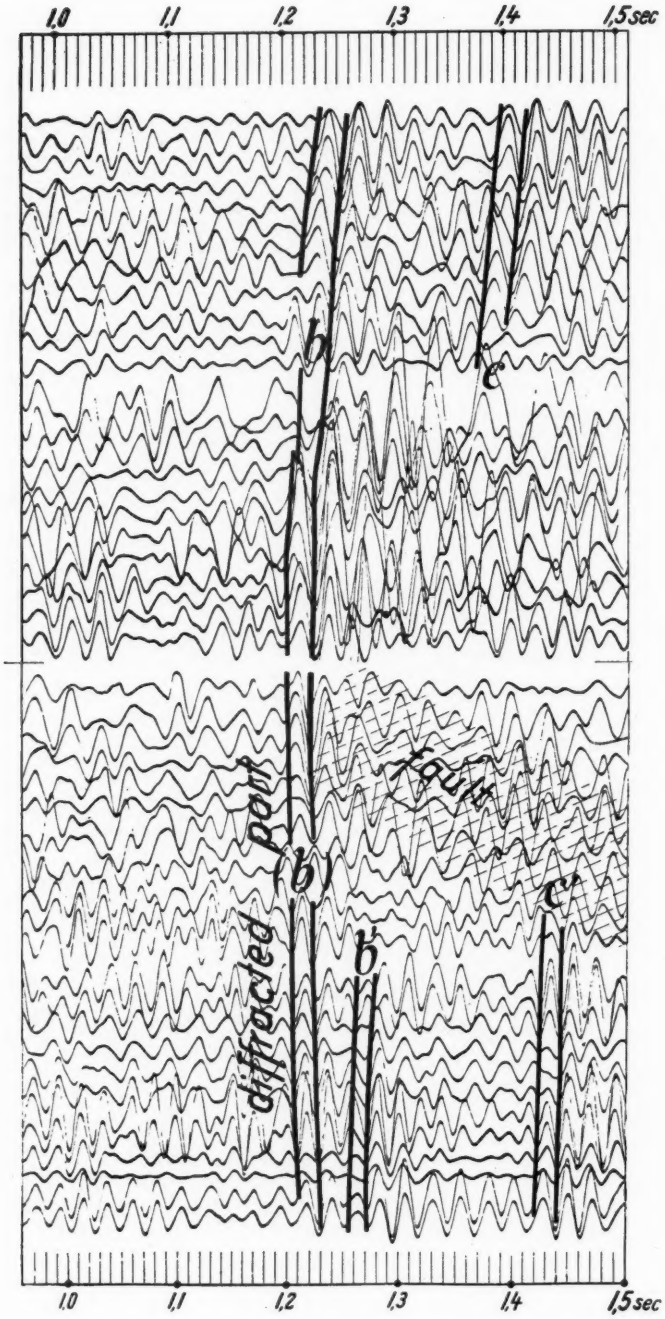
1,0
1,1
1,2
1,3
1,4
1,5 sec
b
c
Fault
diffracted part
b'
b'
c'
1,0
1,1
1,2
1,3
1,4
1,5 sec

FIG. 9

Therefore, it appears very probable that the element (*b*) has been caused only by diffracted radiation and that the fault already begins at the right termination of the horizon *b*. Figures 9 and 10 represent the same again. In addition to that

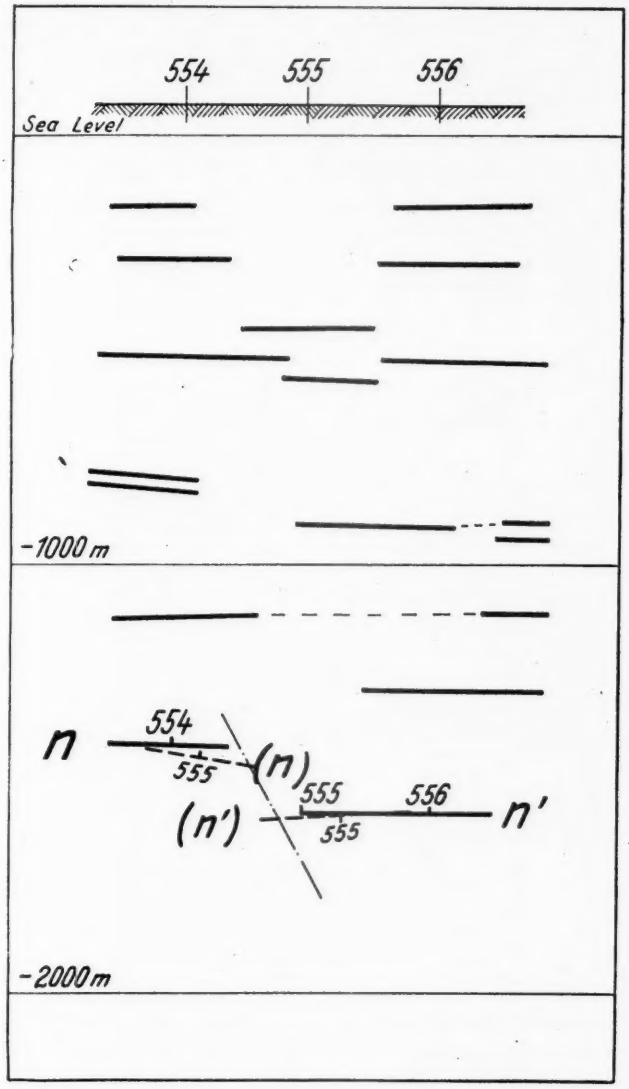

FIG. 10

the overlapping of the diffracted reflection (*n*), coming from the high block, over the reflection *n'* from the deep block is to be seen in Figure 10. Besides, diffracted radiation from the deep block seems to occur in the reflection denoted by (*n'*), too.

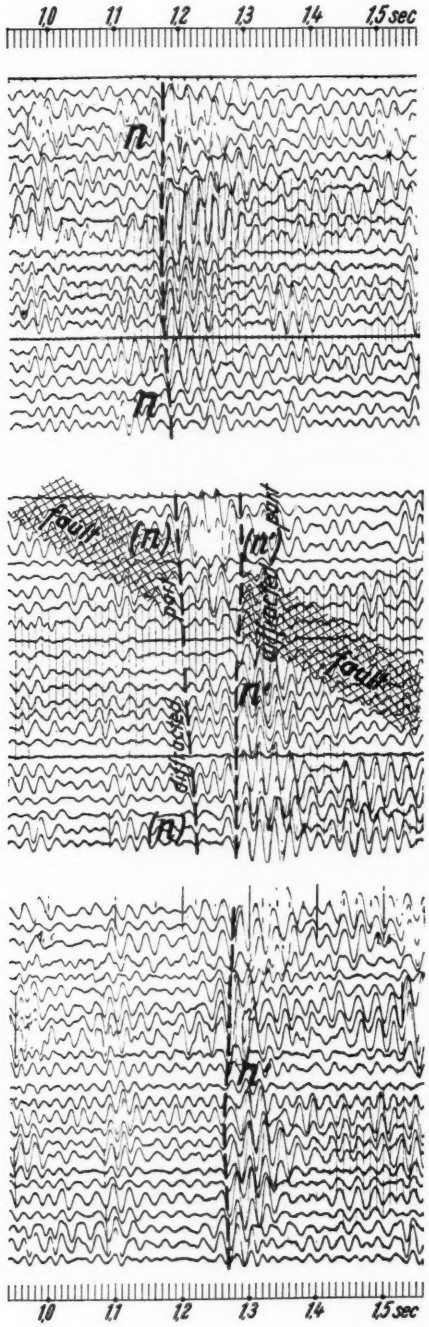

FIG. 11

Figures 12 and 13 again show the same as Figures 10 and 11, but here, overlappings are found not only on one, but on two records,* and apparently diffracted radiation is recorded from the deep block as well as from the high block. Besides, the fault is here not only proved by the horizons n, n', but also by the deeper horizons u, u'.

Finally, a fundamental remark may be made to avoid erroneous inferences. The foregoing discussions and calculations do not only hold good for faults. The

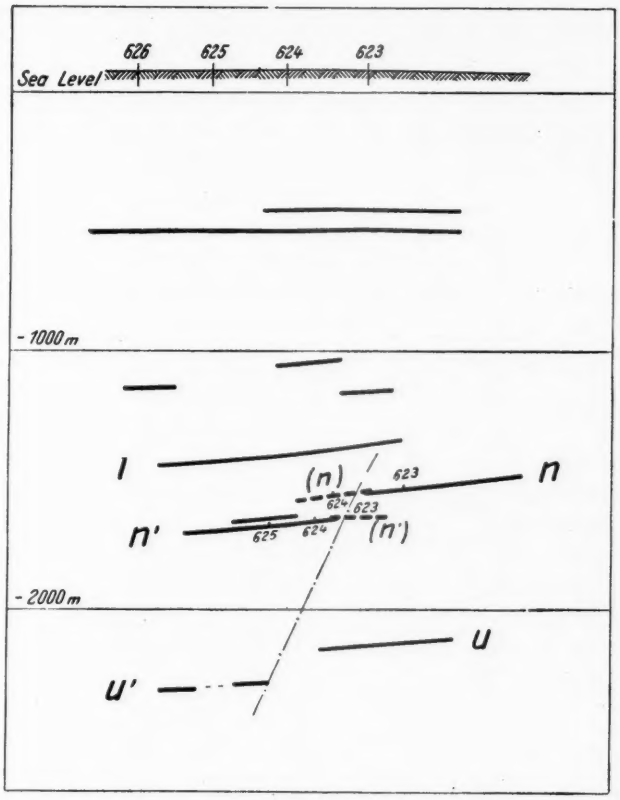

FIG. 12

oscillation pattern shown in Figures 3a to 3c will also be obtained if the reflection horizon under investigation suddenly terminates not because of a fault, but for some other reason; whether it be that the horizon wedges out below a discordance or a sudden change in facies exists, as may perhaps be encountered at a reef. It would, therefore, be wrong to infer, with certainty, the presence of a fault from the existence of similar oscillation patterns as represented in Figures

* The extent of overlapping may considerably increase if the profile crosses the fault not at a right angle, but at an acute angle.

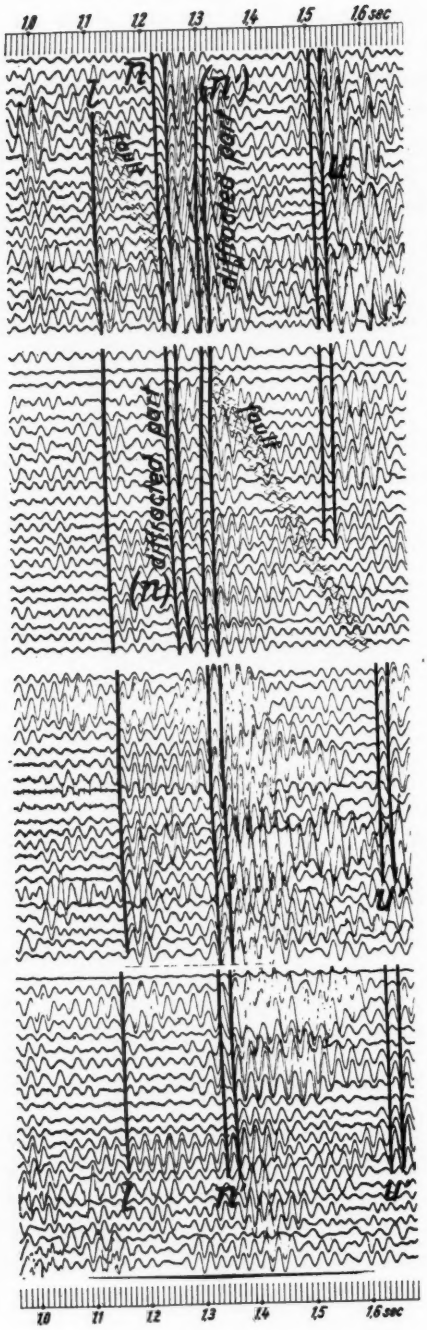
10
11
12
13
14
15
16 sec
diffracted part
diffracted part
diffracted part
10
11
12
13
14
15
16 sec

FIG. 13

3a to 3c. Accordingly, it is not the main object of this paper to assist in the recognition of faults, but, above all, to point to the facts that have to be observed in locating the boundaries of undisturbed blocks. Moreover, the author is of the opinion that this paper should generally remind us of the fact that certain approximations which should not entirely be disregarded are inherent in seismic reflection determinations of geological details.

SUMMARY

Oscillation patterns as obtained according to the diffraction theory are given for a few depths and velocities when records are taken across a fault. From this an apparent overlapping of the shifted blocks will result and the dip will not be quite accurate. These facts are demonstrated by examples gained in practical work. As a result, attention is directed to the approximations involved in plotting the boundaries of the undisturbed blocks.

ACKNOWLEDGMENTS

The author wishes to thank Dr. Lückerath and some of his colleagues for helpful suggestions, and to express his gratitude to Seismos, G.m.b.H. for the permission to publish this paper, and Mr. Tuchel for its translation.

ADDENDUM

There is another reason why the developed pictures of diffracted waves are not quite exact. In *Geophysics*, V, No. 4 (1940) Dr. Ricker proves that the spectrums of seismic wavelets which are produced by blastings change from higher to lower frequencies when time proceeds. Now, I have only considered the frequency of 50 H. Computing more exactly, I should use different frequencies for different depths and moreover I should choose that spectrum belonging to the seismic wavelet when it arrives at the reflecting bed and not when it arrives at the geophone. The consequence is that the effect of diffraction will probably not be so strong as shown in Figures 3b and 3c concerning to the depths of 500 and 1,000 m. As to the depth of 2,000 m the picture given in Figure 3a may be right.

DISCUSSION

MR. WOLF: It is possible that the full implication of the practical value of these diffracted waves has not been realized. The energy of the diffracted wave decreases rapidly in relation to the normal reflected wave and usually it cannot be recognized on the record beyond a small angle from the normal. In some work which we carried out in the U.S.A. some years ago, we demonstrated that it was possible to eliminate the normally reflected waves and to register only the diffracted waves. This was done by placing two geophones, or groups of geophones, 200–300 ft apart and connecting them in opposition. The response to the vertical wave is then zero, but for the inclined diffracted wave the output might be reinforced depending on the angle of emergence and the spacing of the geophones. In

this way we have been able to locate faults, and the diffracted waves have been recorded out to angles of emergence as much as 20°. This work is described in a patent which was issued in 1947.

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THE APPLICATION OF THE REFLECTION SEISMOGRAPH TO NEAR-SURFACE EXPLORATION*

C. F. ALLEN†, L. V. LOMBARDI†, AND W. M. WELLS†

ABSTRACT

The geophysical approach to very shallow exploration problems has been limited, in the main, to electrical, magnetic, electromagnetic, and refraction methods. The reflection seismograph, with its clear advantages of decreased ambiguity and increased resolving power, can be applied to many of these problems.

In the fall of 1951, a Stanford Research Institute crew conducted an experimental reflection survey in Minnesota, mapping with correlation spreads the glacial drift-bedrock interface along seventy miles of line. The interface varied from a few hundred to several hundred feet in depth below surface, and control core holes showed the seismic profile to be essentially correct, where checked. Over-all velocities, determined by shooting core holes, varied from 3,800 feet per second to 5,500 feet per second. Special instrumentation included a high speed camera and a filter peaked at 100 cps. All shots were fired in the air.

The method has obvious applications to mining, engineering, and ground-water problems, and to difficult weathering problems involving thick alluvial, eolian, or glacial debris.

INTRODUCTION

The extension of geophysical tools and methods to fields other than petroleum has long been a subject of interest. The applications have ranged from military uses to searching for buried pipes. Any tool which can aid in the delineation of near-surface geology has immediate applications to mineral exploration and to engineering and ground-water problems.

Magnetic, electrical, electromagnetic, and refraction seismic methods have been applied to near-surface exploration. All have been useful, but all have rather distinct limitations, both in the conditions to which they are applicable and in ambiguity inherent in the method or accuracy potential of interpretation.

The reflection seismograph is by no means applicable to all near-surface exploration problems. It is limited in that it cannot be used for exploration at depths less than some presently unknown minimum, perhaps a few tens of feet, the depth at which other methods begin to lose the precision necessary for shallow work. It is essentially an indirect method of exploration. However, it is applicable to many problems, and it has the advantages of speed, economy, and portability over the core drill, and in general of accuracy and reliability over other presently used geophysical methods.

Practical considerations, particularly the necessity for velocity and other control data, prevent the shallow reflection seismograph's replacing the core drill, just as the conventional seismograph depends on well data for precision. Like conventional seismic work, the method may be used for almost any type of sur-

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vey desired, from close detailing to rough reconnaissance. This paper presents one application.

The problem in this case was to determine the thickness of glacial drift over a large area in Western Minnesota (Fig. 1). The pre-Cambrian iron-bearing formations of the area are buried under several hundred feet of drift. This glacial debris is extremely heterogeneous, ranging from clay sizes to boulders. Its contact with bedrock presents a good, although irregular, reflecting interface. This

FIG. 1. Location Map. Circle indicates general area discussed in this paper.

interface is somewhat complicated locally by the presence of a fossil weathered layer in the bedrock, giving two reflecting horizons separated by only a few feet. Clay lenses in the drift also present reflecting interfaces.

As an experimental alternative to drilling closely spaced core holes along seventy miles of line, Stanford Research Institute conducted a reflection survey along the lines in September and October of 1951.

GENERAL CONSIDERATIONS

Several special considerations are necessary in going from conventional seismic practice to shallow reflection work; one of these is the energy source. In gen-

eral, the trains of surface waves and other disturbances following a hole shot over-ride and obscure any early reflections, which are of far lower energy than the extraneous disturbances. Hole shots therefore were found to be unsatisfactory for this work.

Experiments with various mechanical energy sources, particularly heavy timbers manually operated in pile driver fashion, were not very successful. Although excellent reflections were obtained in some areas, the low energy and small area of application of these mechanical sources severely limit the areas and depths in which reflections can be obtained.

Air shooting provides the most satisfactory energy source yet found. The initial disturbances are relatively small and are essentially over by the time the shallow reflections appear (Fig. 2). Use of an offset shot point avoids difficulty with air-coupled surface waves. The amount of explosive required for shallow work is very small.

It is suspected that very short wave lengths must be used in shallow work. The relation of the reflection coefficient of an interface to thickness of the overlying (transmitting) medium in terms of wave length, or frequency, of energy is rather complex. Simple analyses using steady state conditions are probably more misleading than helpful, especially when these involve one or two dimensional assumptions. Because of the generally heterogeneous nature of transmitting media in the earth, and because of the range of frequencies introduced in a seismic transient, it seems probable that resonant diminution of energy is not the primary factor limiting the frequencies that may be used. It is likely that the duration of the initial pulse producing the seismic transient is one of the more important factors determining the minimum time at which a reflection may be obtained. There does not appear to be any obvious reason for the belief that reflections cannot be obtained at depths less than a wave length.

Empirical experiments in the field showed reflection frequencies of the order of 100 cycles in this area, and a corresponding filter setting was used. Shallow reflections of considerably higher and lower frequencies have been recorded in other areas. Because of the resolution problem, high frequency filtering is desirable where reflection frequency content permits.

There are other problems of instrumentation peculiar to shallow work. A special set of instruments was used, incorporating such features as filter settings peaked as high as 500 cycles. The amplifiers were used without AVC or suppression due to the very short interval between arrival of direct and reflected energies. The camera was speeded up to deliver paper at 4 feet per second and was equipped with high frequency galvanometers. The instruments were mounted in an automobile, but they are compact and portable and can be carried if necessary.

FIELD PROCEDURES AND INTERPRETATION

A spread of five geophones twenty-five feet apart with shot points offset in line three hundred and fifty feet in each direction was selected for this area after

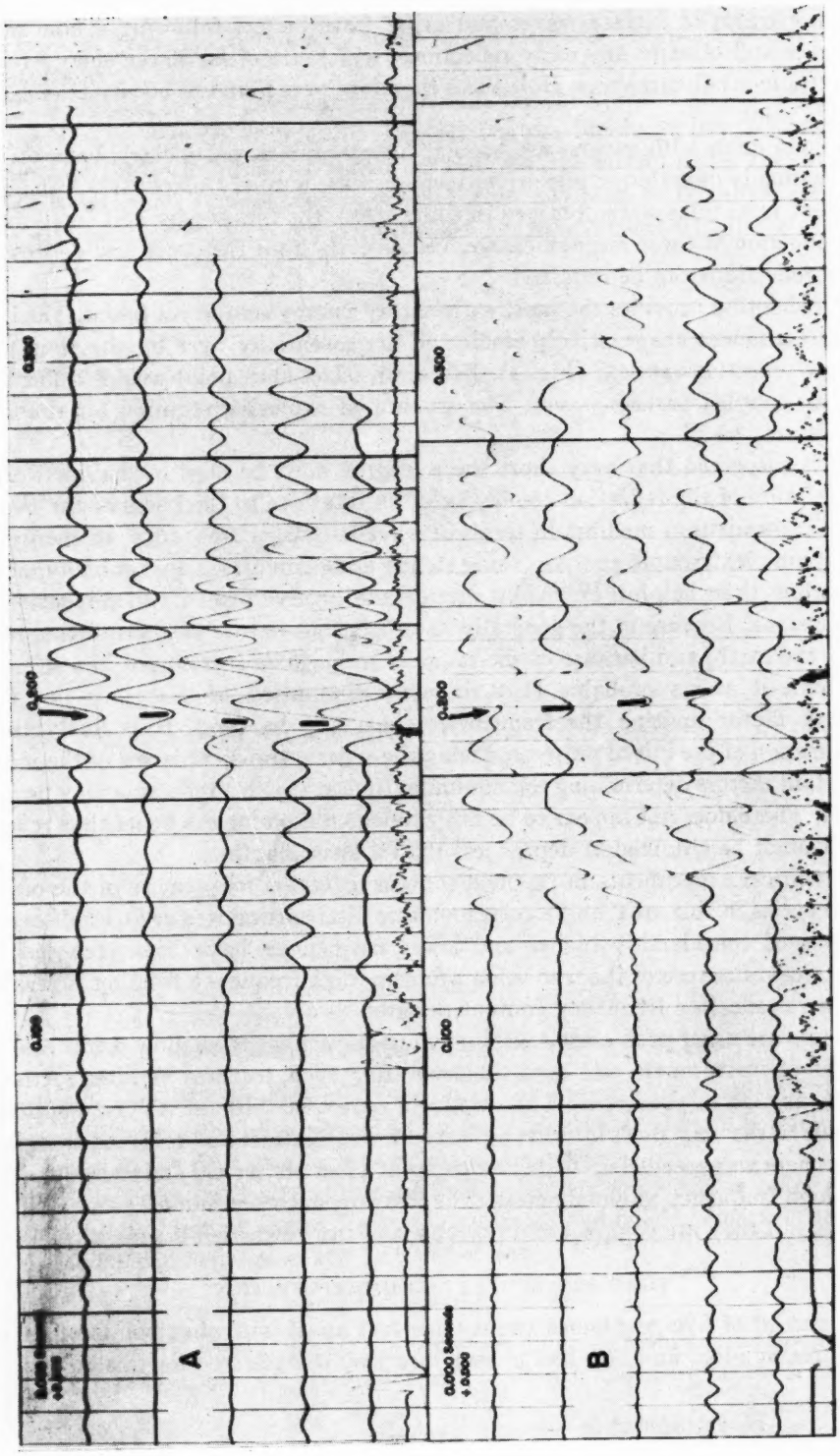

FIG. 2. Shallow reflection records showing (A) low and (B) high first arrival amplitudes. Marked reflection is from surface of bedrock.

considerable experiment. Short spreads were indicated for the work because of the shallow depth and irregularity of the reflecting interface. Split spreads were unsuccessful as the disturbance associated with the air wave lasted long enough to mask any shallow reflections. In order to get as much information as possible from each location, the spread was rotated 90° from the original position and shot again from each end, making a total of four profiles at each recording position (Fig. 3).

The total amount of explosive used for a shot varied from two ounces to two

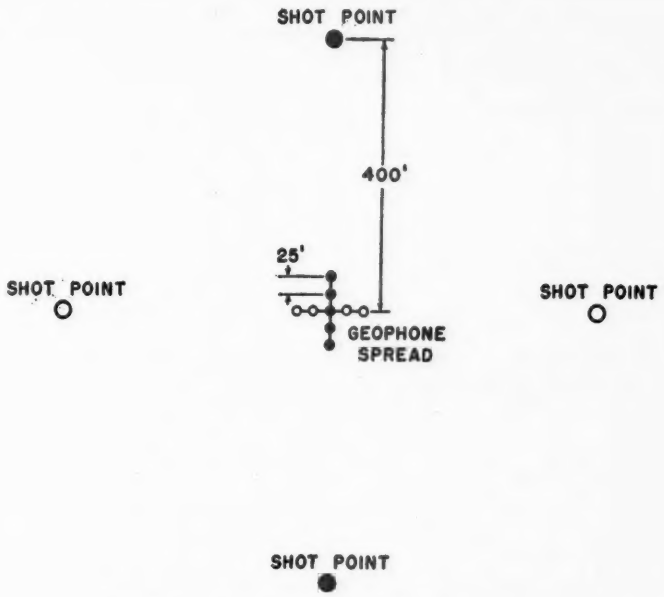

FIG. 3. Field setup used at recording position.

pounds, depending principally on the nature of the immediate ground surface which varied from firm, rocky soils to bogs; the heavy charge was necessary at times to overcome extraneous ground vibrations set up by wind or other disturbances. Almost all of the work was done with two- to four-ounce total charges, placed seven feet above the surface on light-weight steel poles.

Shallow work of this type requires only a small crew; it was found that four or five men could handle all of the work, including interpretation.

The velocity variation in the glacial debris, a heterogeneous mixture of clay, sand, gravel, and boulders, makes the entire problem of velocity critical, and very close attention must be paid to the matter both in the field and in subsequent computation. Velocity measurements were made at the four drilling areas which were available during the period of field work. For these measurements, the shot point was offset two hundred feet from the drill hole. This procedure placed the geophone at the center of the subsurface coverage obtained with the recording

set-up used in the area. It was therefore possible to use the vertical component of velocity, obtained from vertical geophone depths and slant times, directly for routine depth computations without working out vertical velocities and offset corrections.

Velocity gradient across the area amounted to about 50 feet per second per mile, a variation sufficient to cause an error of about 50 percent in calculated depths at one end of the prospect if a constant velocity is used throughout. It was therefore necessary to the interpretation of the data to construct a velocity

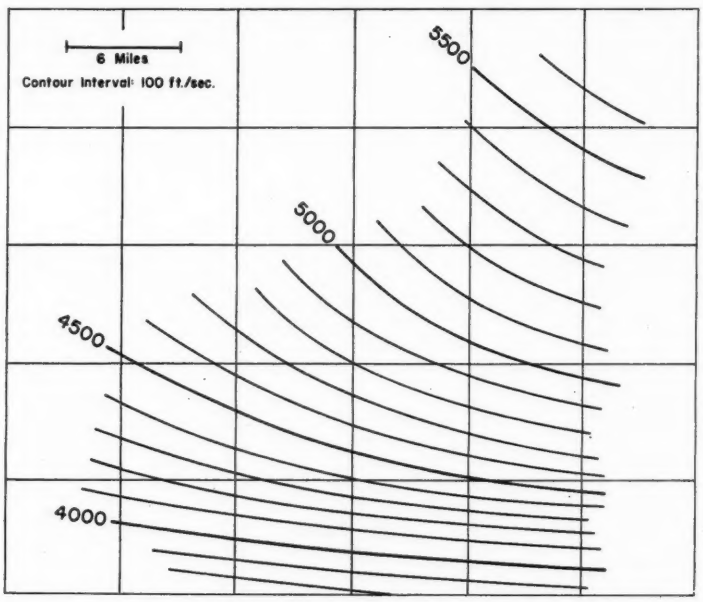

FIG. 4. Average velocity to bedrock across area surveyed in western Minnesota.

contour map and extrapolate the known control since much of the work fell outside the network of drill holes available for survey. The records from each location were computed according to the velocity indicated for that point on the map (Fig. 4).

The interpretation was a straightforward question of spot correlation. Recording position spacing of one-half to one mile gave adequate detail for the reconnaissance type mapping desired. Because record quality was sufficiently high to permit correlation with good reliability, no continuous coverage was obtained. A line of correlated records is shown in Figure 5.

It was possible to check the results of the seismograph survey against the depth of bedrock found in core holes in four areas. It would be desirable to have control at more points to insure representative sampling of the profiles, but the comparison data available indicate that the method is capable of good accuracy.

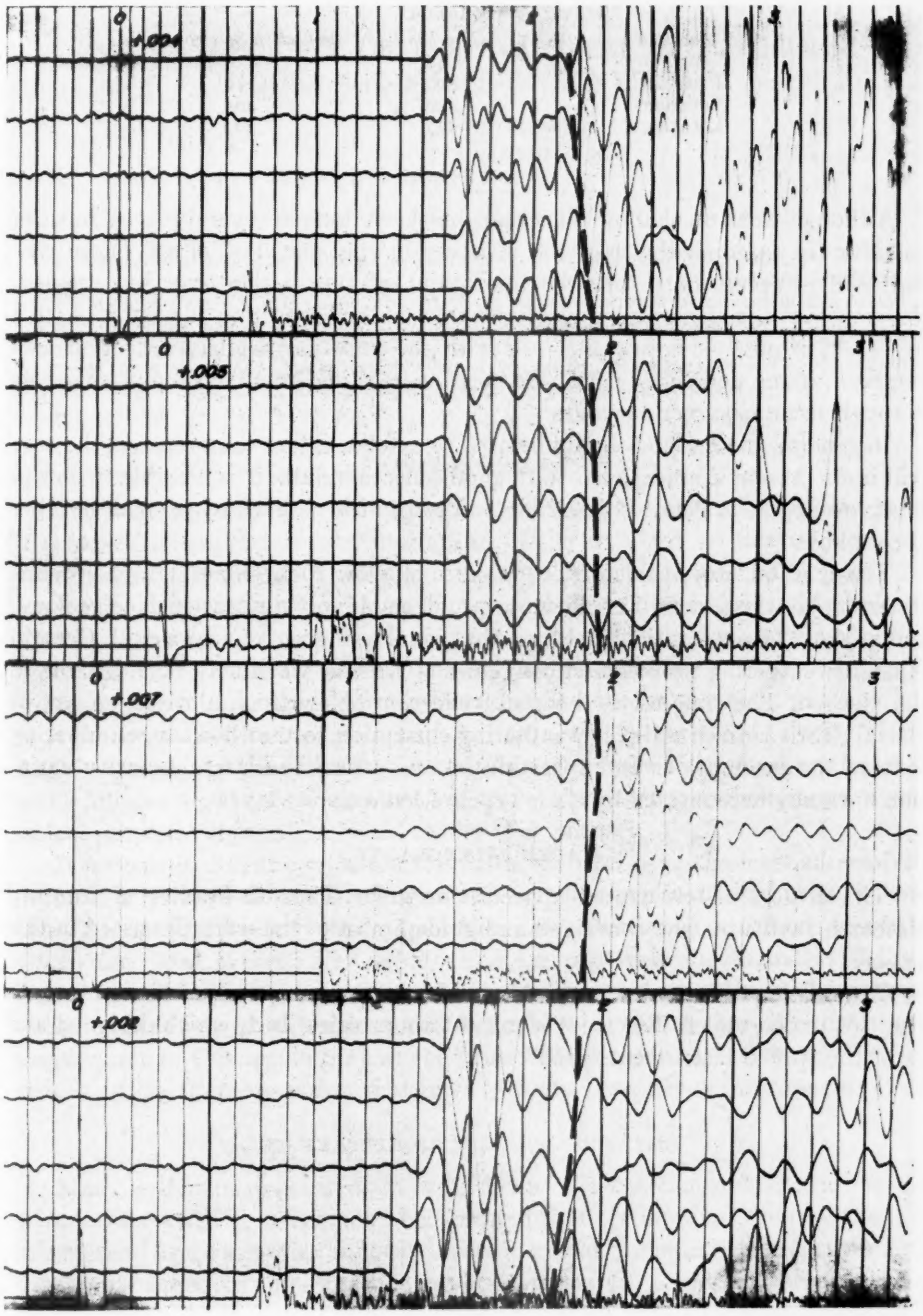

FIG. 5. Correlated records from western Minnesota. Marked reflection is from surface of bedrock.

	Depth of Bedrock	
Location	*Core Drill*	*Reflection Seismograph*
Location 1	544	554
Location 2	600	610
Location 3	450	465
Location 4	427	423

CONCLUSIONS

Although work on shallow reflections has been done in several places, most of the data are based on the results of a survey in only one area; clearly more general trial is necessary before the limitations of the method can be assessed. Nevertheless, the encouraging results of this shallow reflection survey indicate a large field of possible applications. As with the conventional deep reflection seismograph, many degrees of detail are possible, ranging from continuous coverage to rough reconnaissance surveys.

In general, the method should be used to extend, rather than replace, the core drill in its present applications. With good reflection data, it is possible to obtain whatever degree of detail is desired over a large area with a rather small number of core holes.

The method may, therefore, be used in shallow rock, mineral, and groundwater exploration, in civil engineering problems, involving near-surface geology, and in those oil exploration problems that involve the use of a core drill. Certain difficult weathering problems in conventional seismic work may be amenable to the method. The time of the bedrock reflection below thick alluvial, eolian, or glacial debris is itself a direct weathering correction to that horizon, eliminating some of the assumptions and uncertainties on vertical and lateral velocity variation normally necessitated by these types of low velocity layers.

ACKNOWLEDGMENTS

The authors wish to express appreciation to Dr. Thos. C. Poulter, of Stanford Research Institute, who conceived and guided most of the work discussed in this paper.

Appreciation is also due to the M. A. Hanna Company for permission to publish this paper, and to Electro-Technical Laboratories, Inc., which designed and built the special instruments used.

THE INADEQUACY OF THE STANDARD SEISMIC TECHNIQUES FOR SHALLOW SURVEYING*

F. F. EVISON†

ABSTRACT

The seismic method in geophysics has been very thoroughly applied to prospecting for oil, but the techniques developed are not well suited to shallow surveying. A typical shallow survey is described to illustrate some of the shortcomings of the standard seismic techniques in this sphere. A full critique reveals both practical and fundamental limitations, the origin of most of which may be traced to the explosive source. Published data on the form of the explosive impulse suggest that it is inherently unsuitable for shallow surveying. The electromechanical source promises to overcome this difficulty by providing an impulse having any desired frequency and duration.

INTRODUCTION

The spectacular success of the seismic method in the search for oil has tended to distract attention from the limitations of the standard techniques when applied to other problems. Considered generally, the seismic method is capable of much wider application than has so far been attempted. The standard techniques have been concerned almost exclusively with measuring the travel-time of elastic energy between the source and the point of observation; nor has technology produced any adequate means for observing other aspects of elastic propagation, such as those that involve amplitude or frequency rather than velocity alone. But the purpose of the present paper is to show that we are not yet equipped to make full use even of the observation of travel-time over the whole range of geological problems that might be solved by this means.

It is curious that the region of the earth that has been the least successfully explored by means of elastic energy is the first few hundred feet below the surface. The standard seismic techniques have been developed in the course of the search for oil at ever greater depths, and are relatively ineffectual at shallow levels. As will be shown below, the problems of shallow surveying call for essentially more advanced techniques; and it would seem that techniques that are to be adequate in this region may at the same time provide the means of studying aspects of elastic propagation that have hitherto been beyond our reach.

AN EXAMPLE OF SHALLOW SURVEYING

Many writers have pointed out the difficulties that are encountered in shallow seismic surveying. It has come to be accepted that certain limitations of the seismic method as we know it cannot be overcome, and that others can be overcome though not economically. Some classes of problems are accordingly avoided, and

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the possibility of devising radically new techniques to overcome the limitations of the standard techniques has been largely neglected. These limitations are not commonly met with all together in a single problem. But their reality may be better appreciated if an actual seismic survey is described, showing how a number of limitations may be encountered in the field.

The survey, which was carried out by the New Zealand Department of Scientific and Industrial Research, was concerned with measuring the depth of the sand in certain areas of Lyall Bay, Wellington. Where the sand was less than 100 ft deep, an accuracy of a few feet was sought. The rock underlying the sand at

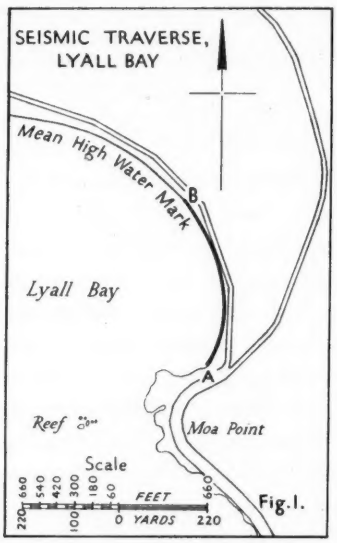

FIG. 1. Region of a Shallow Seismic Survey.

Lyall Bay is greywacke, a strongly indurated sandstone which is not markedly magnetic; and the sand itself is saturated with sea-water. Thus, neither magnetic nor electrical measurements could be expected to give the required information. On the other hand, the velocity of sound in greywacke is usually rather high, promising a good contrast with the velocity in saturated sand, so that the seismic method was clearly the most suitable for the problem.

The part of the survey that will be described in some detail here was a traverse along Lyall Bay beach, running north from Moa Point, as shown by the line *AB* in the accompanying map (Figure 1). Judging from the geology of the area, north was also approximately the direction of dip of the sand-greywacke interface. This traverse was the main part of a reconnaissance of the area, undertaken in order to reduce to a minimum the amount of work necessary out in the Bay. A portable refraction apparatus was used for the survey, with six geophones and a 500-ft. cable.

Figure 2(a) shows the observed travel-time plotted against distance. Shot 1 was fired at the greywacke-sand contact at the south end of the traverse. Two complicating features of the problem were clear from a general inspection of the time-distance relations: the dip of the greywacke surface was far from constant; and at the north end of the traverse the observed refractions arose from a deeper stratum with a higher velocity. From the curves of Figure 2(a), together with data from other shots in the neighborhood, the three velocities were found to be 5.7 ft/millisec for the sand, 8.5 ft/millisec for the first refractor, and 11.7 ft/millisec for the second refractor.

INTERPRETATION BY STANDARD FORMULAE

The time-distance data were analyzed as far as possible using the standard refraction formulae (1). Thus, from the point where the time-distance curve for the direct wave intersects that for the first refractor, the depth of the refractor was calculated at shot-points 2, 3, 4, and 7. These depths are shown plotted in Figure 2(b). The greatest depth calculated in this way was 50 ft at shot-point 4. These determinations could probably have been carried to a somewhat greater depth, if desired, by more detailed shooting to the north of shot-point 4; but at shot-point 6 there was no longer any indication of the first refractor. In any case, serious inconsistencies could readily be noticed between the calculated depths and other information contained in Figure 2(a); for example, shots 1 and 2 indicated a northerly dip, whereas the depth indicated at shot-point 3 was zero.

The theory behind the standard formulae for interpreting seismic measurements assumes that, apart from minor irregularities, the dip of a refractor is constant for a sufficient distance from the shot-point for the slope of the time-distance curve to be properly established. There is clear evidence in Figure 2(a), however, that the first refractor was not sufficiently uniform. Shots 3 and 4, for example, indicated dips of 11 degrees and 2 degrees respectively, for the same vicinity; and the contrast between the time-distance curves for shots 5 and 7, which were only 100 ft apart, showed that the dip must change very rapidly to the north of shot-point 4.

Evidently the standard method of interpretation could not be applied to the measurements with any confidence in the accuracy of the results. It was necessary, therefore, to resort to a more fundamental study of the time-distance observations.

INTERPRETATION FROM FIRST PRINCIPLES

In the standard seismic procedure, a large number of observations are made, so that the salient features of the profile may be readily extracted by graphical and algebraical means. In this way, although more information is often collected than is used, the interpretation is rapid, and country may be covered at a reasonable rate. This procedure could not be followed in the present survey, but since the area to be examined was small, it was practicable to make an exhaustive anal-

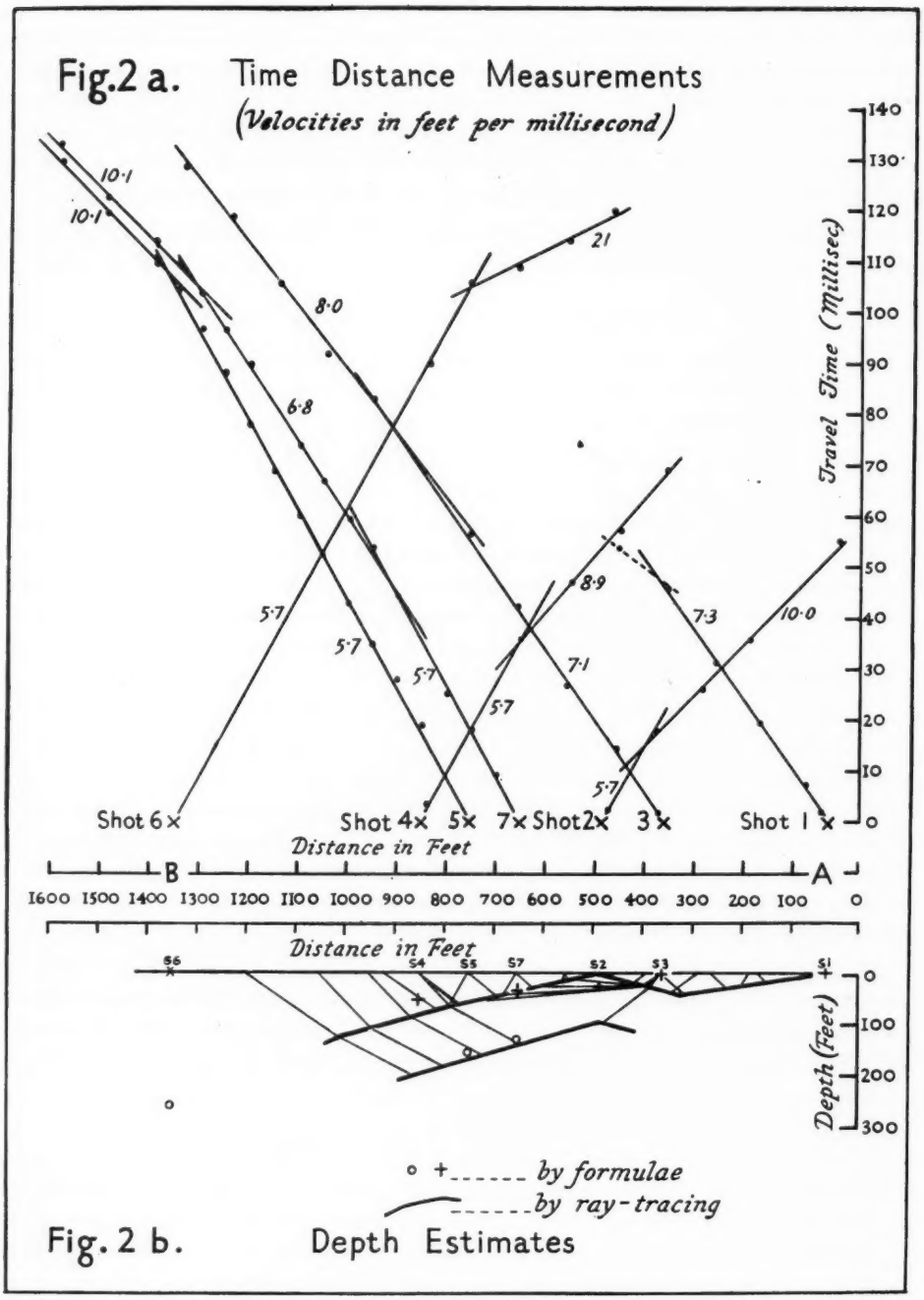

FIG. 2. Shallow Refraction Measurements and Interpretation.

ysis of the measurements. This was done by building up a scale drawing of the vertical geologic section with the help of the various ray-paths, constructed according to the well-known law of refraction. By adjusting the diagram until the travel-time for each ray-path agreed with the corresponding travel-time observed seismically, an interpretation was obtained which made independent use of the information from each geophone for each shot. The diagram, including some of the ray-paths, is shown in Figure 2(b).

By this laborious procedure, the first refractor was mapped out to a point 200 ft beyond the last determination obtained by the standard formulae. The failure of this refractor to produce first arrivals from shots 5 and 6 showed that a further rapid increase of dip occurred beyond this point. The profile, as is shown in Figure 2(b), revealed errors of up to 35 ft in the depths calculated from the standard formulae. The required maximum depth of 100 ft was reached at a point 70 ft to the north of shot-point 4; and it would have been impossible, in any case, to extend the profile much further.

For the second refractor, approximate depths had been calculated at shot-points 5, 6, and 7 by the standard formulae, ignoring the intermediate layer. This refractor was also traced diagrammatically for a short distance, from the travel-time data for shot 3. The results are shown in Figure 2(b).

The two profiles drawn could not be extended any further to the north, since the observations were incapable of establishing either refractor independently of the other; the travel-time measurements in this region could be accounted for by postulating the positions of the refractors in any of a variety of ways.

PRACTICAL LIMITATIONS OF THE STANDARD TECHNIQUES

Let us now consider the limitations of the seismic method at its present stage of development, especially when it is applied to shallow problems such as that just described. The difficulties that arise are partly practical and partly fundamental.

Certain limitations of the standard seismic techniques may sometimes be overcome by special procedures, but these are often too laborious to be economical. For example, in regions of irregular dip, such as that of the survey described above, measurements that are more readily interpreted may be obtained by shooting across the required profile, that is, in the direction of strike. If this direction is not too variable, accurate depths may be calculated by the standard formulae, allowing for the fact that a depth so calculated is that along the normal to the refractor, and not the vertical depth. But, especially since frequent backshots are needed to verify the direction of strike, this procedure lacks the usual advantage of the refraction method in covering many hundreds of feet with each shot. In the case of the present survey, the procedure would have been particularly awkward, because access could not readily be gained to the ground east of the traverse, and to the west lay the sea.

The difficulty of mapping irregular interfaces, as illustrated above, is especially serious in shallow surveying. Shallow strata tend to be less uniform because

they are more susceptible to small-scale geological influences. For example, the greywacke surface traced in the above survey is believed to have been exposed until quite recent times. And the practical significance of a given irregularity is usually inversely proportional to its depth. A feature having the order of relief shown in Figure 2(b) would be of no account at the depths normally surveyed by the seismic method.

Seismic apparatus, for both shallow and deep surveying, is usually designed to measure travel-times to the nearest millisecond. In general, the accuracy with which a travel-time may actually be measured increases with the size of the explosive charge and with proximity to the shot-point. Distances are, of course, less in shallow surveying; but usually the charge must also be reduced, for the sake of safety and convenience. Thus, in practice much the same degree of timing accuracy is attained for all depths; and, since velocity seldom increases in proportion to depth, it follows that the relative accuracy of the seismic method deteriorates at shallow levels.

The method of ray-tracing used above is not only tedious, but is less accurate for irregular interfaces than is the standard method of interpretation for regular interfaces. When dip is constant, the time-distance curve is linear, and although travel-times are read to the nearest millisecond, the net experimental error is only a fraction of a millisecond. But when each travel-time is interpreted separately, it is difficult in practice to reduce the millisecond reading error; and in the present case this represented an uncertainty of up to 20 ft in the position of either interface at a point of refraction.

FUNDAMENTAL LIMITATIONS OF THE STANDARD TECHNIQUES

As is well known, the refraction technique can give no direct indication of an interface at which the deeper rock has the lower velocity, since in such a case the energy is refracted downwards. This condition is perhaps more likely to occur at deep than at shallow levels, and may usually be dealt with by adopting the reflection technique.

The difficulty just mentioned follows from a natural law, but it arises only in abnormal geological circumstances. Certain other fundamental limitations of the present seismic techniques are much more serious for practical surveying, especially at shallow levels, and yet they derive not from the necessities of physics but rather from a failure to recognize these necessities.

First, it may be remarked that much of the difficulty experienced in the survey described above could have been avoided by observing reflected instead of refracted energy. The standard reflection technique, however, has proved itself incapable of detecting interfaces shallower than about 500 feet. But the power of the refraction technique to resolve the details of an interface may be quite inadequate for a shallow survey.

Again, it is impossible to resolve two successive interfaces when the distance between them is less than a certain fraction of their depth. For in the refraction

technique, as the northern part of the above survey illustrates, the upper interface may fail altogether to provide first arrivals; and later arrivals cannot normally be used. In the reflection technique, on the other hand, it is the lower interface that is missed, the arrival being obscured by that from the upper interface, just as all shallow reflections are obscured by direct waves and shallow refractions.

The origin of these limitations is in the nature of the explosive impulse. As a convenient and powerful source of elastic energy, dynamite has contributed greatly to the success of the seismic method as an aid to oil-prospecting. Nevertheless, an examination of the explosive impulse shows that its usefulness is seriously limited, both for shallow surveying, and for extending the seismic method beyond the simple measurement of travel-time.

THE FORM OF THE EXPLOSIVE IMPULSE

It is difficult to observe the development of the complex disturbance that radiates from an explosion. The most extensive theoretical and experimental work that has been published on this subject is that of J. A. Sharpe (2). It may reasonably be assumed that at a certain stage the radiating energy takes on the form of a spherical elastic wave, and Sharpe has shown that the dominant frequency of this wave is inversely proportional to the radius at which it is set up, and directly proportional to the velocity of propagation. Sharpe's analysis accounts for many well-known relations connecting the amplitude and dominant frequency of the explosive impulse with the size of the charge, the manner of laying it, and the nature of the rock. It does not explain, however, the observed duration of the impulse. According to the analysis, an assumed non-oscillatory application of pressure at the critical radius produces an impulse containing one, or at the most two cycles, whereas the impulse observed in seismic records, including those published by Sharpe, persists for many cycles.

A well-known effect illustrated by Sharpe from his observations near the source is the lowering of the dominant frequency as the impulse travels outwards. This is usually attributed to selective frictional attenuation in the rock, but the very high rate of attenuation deduced by Sharpe suggests the presence of other factors in his observations. Sharpe's estimate of about 6 db attenuation per 50 ft for frequencies around 1,000 c/sec., in rocks with velocities between 8 and 10 ft/millisec, is many times greater than other published values of frictional attenuation. The present writer obtained the value 0.75 db per 50 ft for the frequency 600 c/sec in chalk *in situ*, the velocity being only 7.66 ft/millisec. (3). Born's measurements on samples in the laboratory indicated the value of 0.70 db per 50 ft, for the frequency 1,000 c/sec, in shale of velocity 13.0 ft/millisec (4). It would seem, therefore, that much of the attenuation observed by Sharpe was probably due to the closeness to the source at which his measurements were made. Both this peculiarity of Sharpe's observations and the invariable occurrence of many cycles in the impulse, as described above, suggest that some relation between fre-

quency and efficiency of propagation near the source may be important in determining the character of the explosive impulse.

Some idea of the potential resolving power of the explosive impulse may be gained from the observations of Sharpe. In order that two adjacent arrivals in seismic record may be distinguishable, the earlier arrival must, in general, have come to an end before the later one commences. Some writers have stipulated only that the initial build-up of the earlier arrival should be completed, but this would clearly be insufficient if the earlier arrival were very much the stronger of the two (5).

Sharpe's observations concerned the particle velocity produced at various distances by exploding $\frac{1}{8}$ lb dynamite in a rock of velocity 8.5 ft/millisec. This velocity is fairly typical of competent rocks at shallow levels, but the charge was smaller than usual, and therefore the higher frequencies would be more prominent. At 15 ft the dominant frequency was about 1,500 c/sec and the duration of the impulse about 3 millisec; at 100 ft the dominant frequency had fallen to about 200 c/sec and the duration had increased to 50 millisec. The significance of these observations may be considered, for simplicity, in relation to a hypothetical reflection survey using a geophone near the shot-point, but assuming no interference from direct or refracted arrivals. If dominant frequencies were observed, resolution would be very poor. For example, a reflection from $7\frac{1}{2}$ ft depth would obscure all further reflections above a depth of 20 ft, and a reflection from 50 ft depth would obscure all further reflections above 260 ft.

Alternatively one might try to secure the desired degree of resolution, above a specified depth, by filtering out of the received vibrations all frequencies below a suitable limit. Thus, if it were not required to distinguish reflectors separated by any distance less than one-tenth of their depth, it would be sufficient, in the circumstances of Sharpe's experiments, to exclude frequencies below 1,500 c/sec for measurements down to 100 ft, and to exclude frequencies below 200 c/sec for measurements down to 2,000 ft. This would pose a difficult filtering problem, since the amplitude of the excluded band would be very much greater than that of the accepted band. It is even doubtful whether the desired frequency would have sufficient amplitude to be detected at all; and if the charge size were increased to give more energy, the preponderance of low frequencies would be still greater.

The conclusion is that the explosive impulse is inherently unsuitable for detailed shallow surveying, and that no amount of manipulation, whether at the shot-point or in the receiver, is likely to effect much improvement in the resolving-power of the standard seismic techniques. A recent writer has recognized the need "to shorten and simplify the input signal," and has expressed the view that "the elimination of the non-linear displacements in the vicinity of the shot-point appears to be an obvious approach" (5). It only remains to acknowledge that the disturbance generated by exploding dynamite is essentially non-elastic and essentially complex.

A SUGGESTED ALTERNATIVE SOURCE

What limits the resolving power of the standard seismic techniques is the low frequency energy that is invariably generated by a dynamite explosion; yet this is precisely the part of the explosive impulse that has hitherto been used with such success. An ideal source for shallow surveying, and indeed for broadening the whole scope of this branch of geophysics, would be one capable of generating an impulse with any desired frequency and of any desired duration. With such a source, and a receiver with variable frequency and band-width, only energy in a form appropriate to the problem need be generated, and all the significant energy reaching the receiver could be used.

As far as the form of the impulse is concerned, an electromechanical source with which the author has experimented is of the type needed (6). The difficulty is to produce enough energy. But unlike the limitations of the explosive impulse, which are fundamental, this difficulty is so far only technical. It has two aspects; the electrical problem of generating a very large current at frequencies between, say, 200 c/sec and 1,000 c/sec; and the mechanical problem of coupling the machine rigidly to a sufficiently large area of the ground. The original apparatus, which developed a current pulse of some 3,000 amp r.m.s. and was coupled to an area of 1.35 sq ft, gave rise to adequate reflections down to several hundred feet in chalk (3). A new apparatus is being designed to develop a current pulse of 6,000 amp r.m.s., and to be coupled to an area of 12.5 sq ft. These improvements should increase the power of the apparatus by a factor of about 35. The earlier experiments were carried out in specially chosen conditions, but the increased power should render the technique applicable in at least the more favorable conditions normally met in the field. As with the standard techniques, the greatest difficulties, on the one hand, will be presented by an unconsolidated surface layer, while, on the other hand, it should be easy to couple to water-saturated ground—in this case by mounting the machine on a large metal plate.

The author wishes to thank the New Zealand Department of Scientific and Industrial Research for permission to describe the Lyall Bay survey, and Dr. E. I. Robertson for a number of useful suggestions.

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A STUDY IN INTEGRATION OF GEOLOGY AND GEOPHYSICS*

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ABSTRACT

The need for cooperation between and integration of geology and geophysics in the search for petroleum is illustrated by application and analysis in the Kilgore Area, Gregg and Rusk Counties, Texas. Independent interpretations of geologic structure from regional geology and reflection seismograph survey are presented and evaluated. The geologic interpretation is revealed to be based on accurate data of insufficient density and distribution to reveal even sizeable structural features. The reflection seismograph interpretation of structure reveals both small and large features which are of doubtful validity due to questionable time-depth relationships over the area. An integrated interpretation utilizing the geological data to define velocity limitations for the seismic time-depth relationship is attempted and a theoretical corrected structural interpretation is presented. The following conclusions are reached:

(1) Standard methods of exploration for petroleum often produce incorrect results; the limitations of geologic and reflection seismograph methods do not overlap; therefore, it is possible to utilize the maximum interpretation of geological data as a guide to the velocity variations which affect the seismic interpretation.

(2) Lack of sufficient velocity information can be a serious handicap to utilization of the reflection seismograph method; therefore, every opportunity to obtain additional velocity information should be utilized.

(3) The Kilgore Area illustrates that existing seismic interpretations of structure that are in disagreement with known geologic data may often be recomputed for a correct interpretation at a small extra cost.

INTRODUCTION

The geologist and geophysicist pursue a common goal in the applied science of oil exploration. Yet, often the interpretation and application of geological and geophysical data lead to costly conflicting and erroneous evaluation of a prospective oil producing area. Nettleton (1949), Green (1948) and many others have made a strong plea for closer cooperation between geologists and geophysicists, advancing suggestions for the accomplishment of a working cooperation. This paper has been prepared to provide a demonstration of the practical application of these suggestions.

The first principle of this cooperation is to recognize the limitations of each method of investigation. A geological interpretation is usually inadequate on the basis of density and distribution of data. A geophysical interpretation is inadequate because it is based on the time-depth relationship of a type geologic section; therefore, any change of lithology from this type section will introduce an error which will distort and may hide the true structural relationship. Time is the only factor that the reflection seismograph measures. The travel time to a reflecting horizon is accurate, but can be used to represent geologic structure only if the

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correct velocity conversion is applied to obtain depth. The early geophysical successes were in large measure due to the fact that comparatively large vertical differences in structural position of a formation were easy to define. Continued success will require the consideration of possible structural and lithologic variations from the simple type section before a seismic interpretation of geologic structure is made.

The second principle of cooperation is the development of an integrated interpretation utilizing the geological data to provide a maximum refinement of the assumptions which are necessary to interpret the geophysical data. In this manner the final geological evaluation of an area will have utilized to the greatest possible extent all of the data available. This is, after all, a well known principle, but one which has not been successfully applied because the maximum geological interpretation is not ordinarily given to the geophysicist *before* he attempts to evaluate his physical data in terms of geologic structure.

This paper illustrates the results that may be obtained by thorough integration of geological and geophysical data. In order to provide an adequate basis for comparison, independent geological and geophysical interpretations will also be given.

The problem of finding and securing data of an area which could be published without endangering the economic interests of the owner was a difficult one. As a result, the data which were made available provide only nominal results; nevertheless, the basic principles of geological-geophysical integration may be adequately demonstrated and their true value appreciated.

The area selected for illustration is located in Gregg and Rusk Counties, Texas. Figure 1 shows the location and surface geology of the area. An interpretation of a reflection seismograph survey of this area was released for this investigation.

AN INDEPENDENT GEOLOGICAL INTERPRETATION

The Kilgore Area is located in the East Texas Basin on the west flank of the Sabine Uplift. Both of these structures are well known features of the Gulf Coastal Plain and have been discussed at length by many authors. Reference is made to them in the bibliography. After the work of these investigators, it was a simple matter to prepare a cross section from well data and portray the general geological history of the area. Figure 2 shows the results of a compilation of this data.[1]

This examination was confined to formations of Cretaceous and younger age.

[1] Formation and group names on the cross section (Fig. 2) were obtained from the following sources: Clairborne and Wilcox groups, Murray and Thomas, 1945; Midway, Navarro, and Taylor groups, Decker, 1931; Austin, Eagle Ford-Woodbine, Washita, and Fredericksburg groups, Bailey, Evans, and Adkins, 1945; Trinity group, with the exception of the Pettit and Travis Peak formations, Imlay, 1945; the Pettit and Travis Peak are formation names in use in East Texas in place of Sligo and Hosston of the Arkansas-Louisiana section.

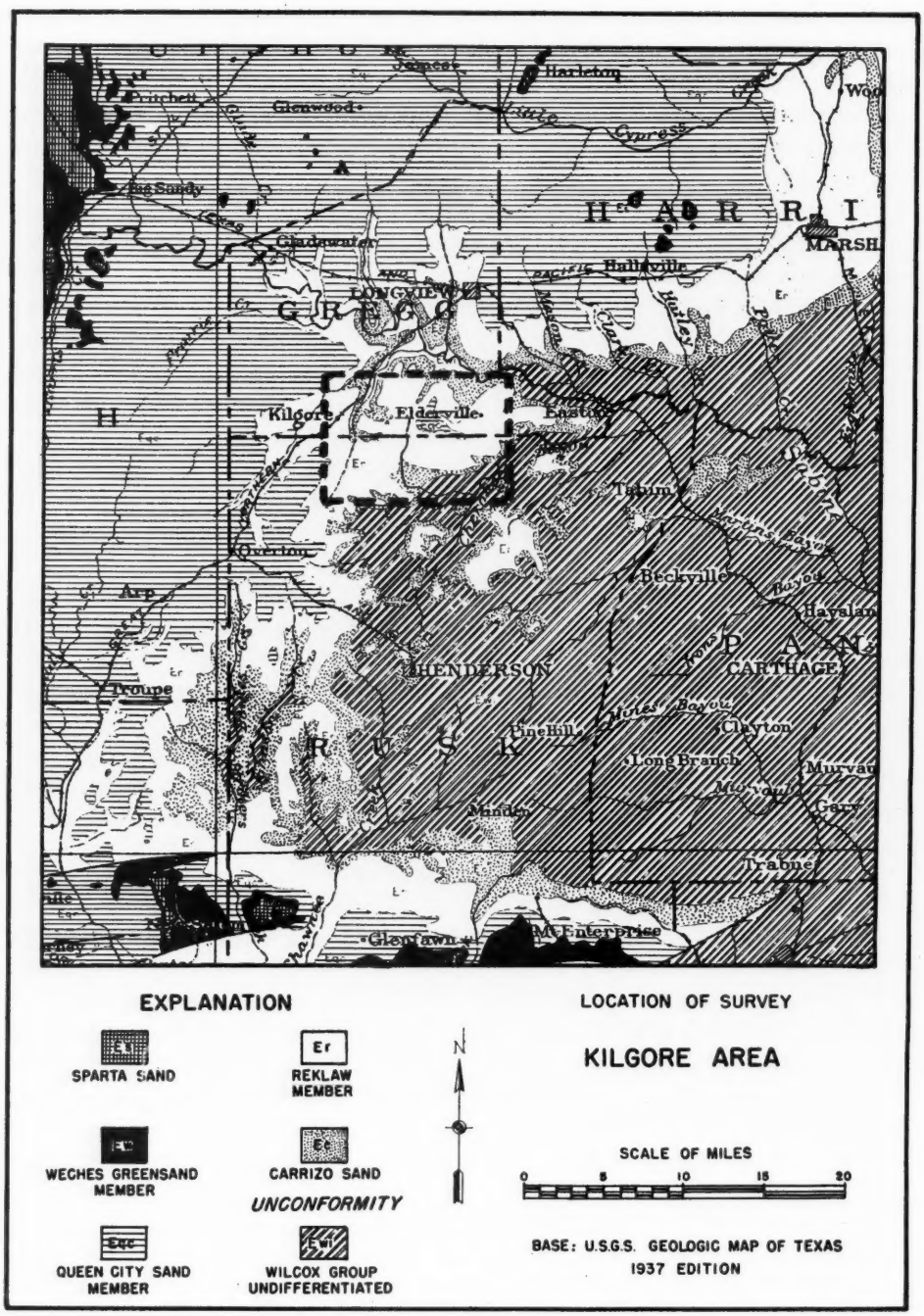

FIG. 1. Location of Survey, Kilgore Area

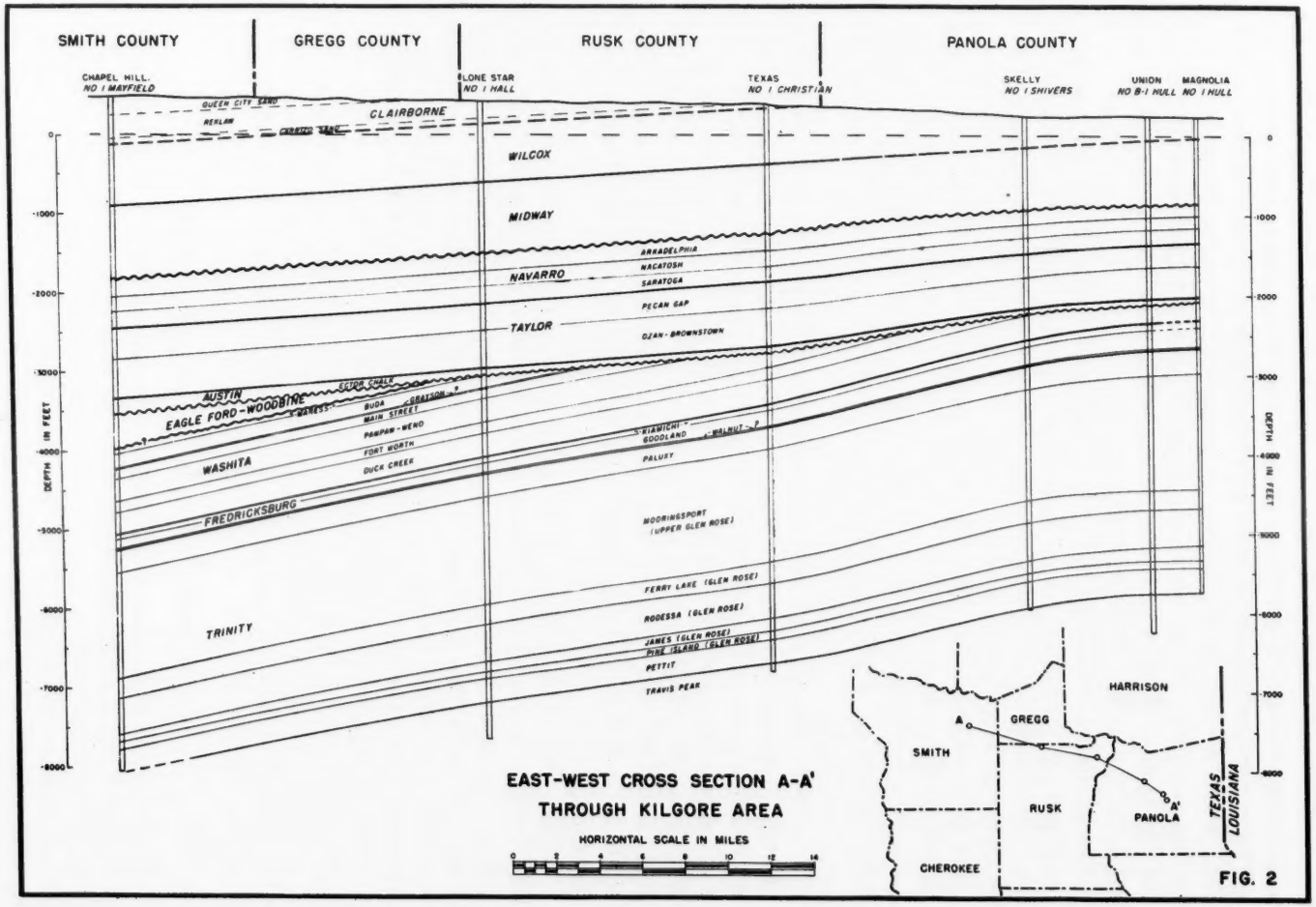

FIG. 2. East-West Cross Section through Kilgore Area

As revealed on the section, the formations of the Lower Cretaceous are conformable and represent similar conditions of deposition over a widespread area.

The warping of the earth's crust which caused the original formation of the Sabine Uplift occurred after the close of the Lower Cretaceous (Sellards, 1932). The regional uplift covered extensive portions of Arkansas. Louisiana, and Texas, with the Monroe Uplift paralleling the eastern flank of the movement as the Sabine Uplift parallels the western flank.

The uplifted Lower Cretaceous formations were eroded to furnish much of the sediment in the adjacent East Texas Basin. The truncation to a plain of low relief in an advancing sea was accomplished by Austin time, when the Ector chalk was deposited over the whole area.

During later stages the whole region was subjected to fluctuation of sea level and minor unconformities resulted. At the present time the Wilcox sand (Eocene) is the oldest formation exposed over the uplift (see Fig. 1). The outcrop of the Carrizo sand roughly delineates the boundary between the Sabine Uplift and the East Texas Basin.

In order to evaluate the subsurface structures of the Kilgore Area, subsurface structural maps were prepared for fifteen different surfaces. However, a comprehensive understanding can be achieved with interpretations of structure at only three horizons. These are top of Ector formation (Fig. 3), top of Goodland formation (Fig. 4), and the base of the James formation (Fig. 5). Isopach contours between the top of Ector to top of Goodland formations (Fig. 6), and top of Goodland to base of James formations (Fig. 7) show the interrelationships of these surfaces.

No large anomalous features are revealed. The slight nosing in the vicinity of the Tidewater-Seaboard No. 1 Bird well is reflected on all horizons. Within the limits of the Kilgore Area (indicated by dashed line) there is interpreted a regional dip slightly to the north of west, the amount varying with depth, but much greater for the Lower Cretaceous formations than for the Upper Cretaceous formations. It is to be pointed out that well spacing, except in the neighborhood of the fields, is approximately one well per forty square miles. There are numerous shallow wells (not shown) which were abandoned before reaching the Lower Cretaceous; thus information derived from them is of lesser value. This evaluation of the geologic structure is an excellent illustration of the limitations imposed by subsurface data.

AN INDEPENDENT GEOPHYSICAL INTERPRETATION

The results of a reflection seismograph survey in the Kilgore Area are shown by Figures 8 and 9. Contours are drawn on the structural position of reflecting horizons identified as the top of the Goodland formation and the base of the James formation. Computations for these results were made using a sub-weathering velocity of 8,000 feet per second to correct to a reference plane 200 feet above sea level. A time-depth curve based on a velocity determination in the Magnolia

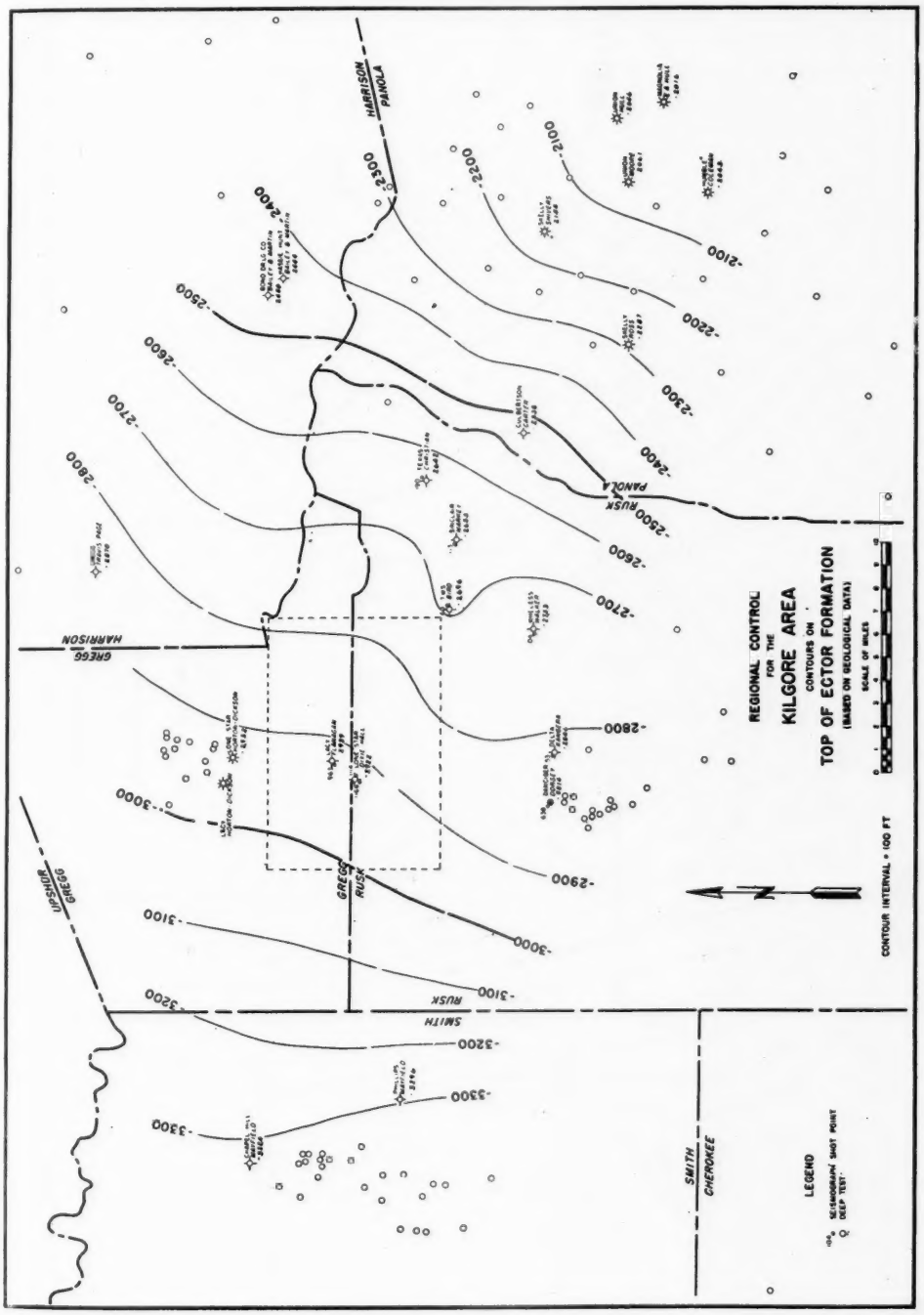

FIG. 3. Regional Control for Top of Ector Formation

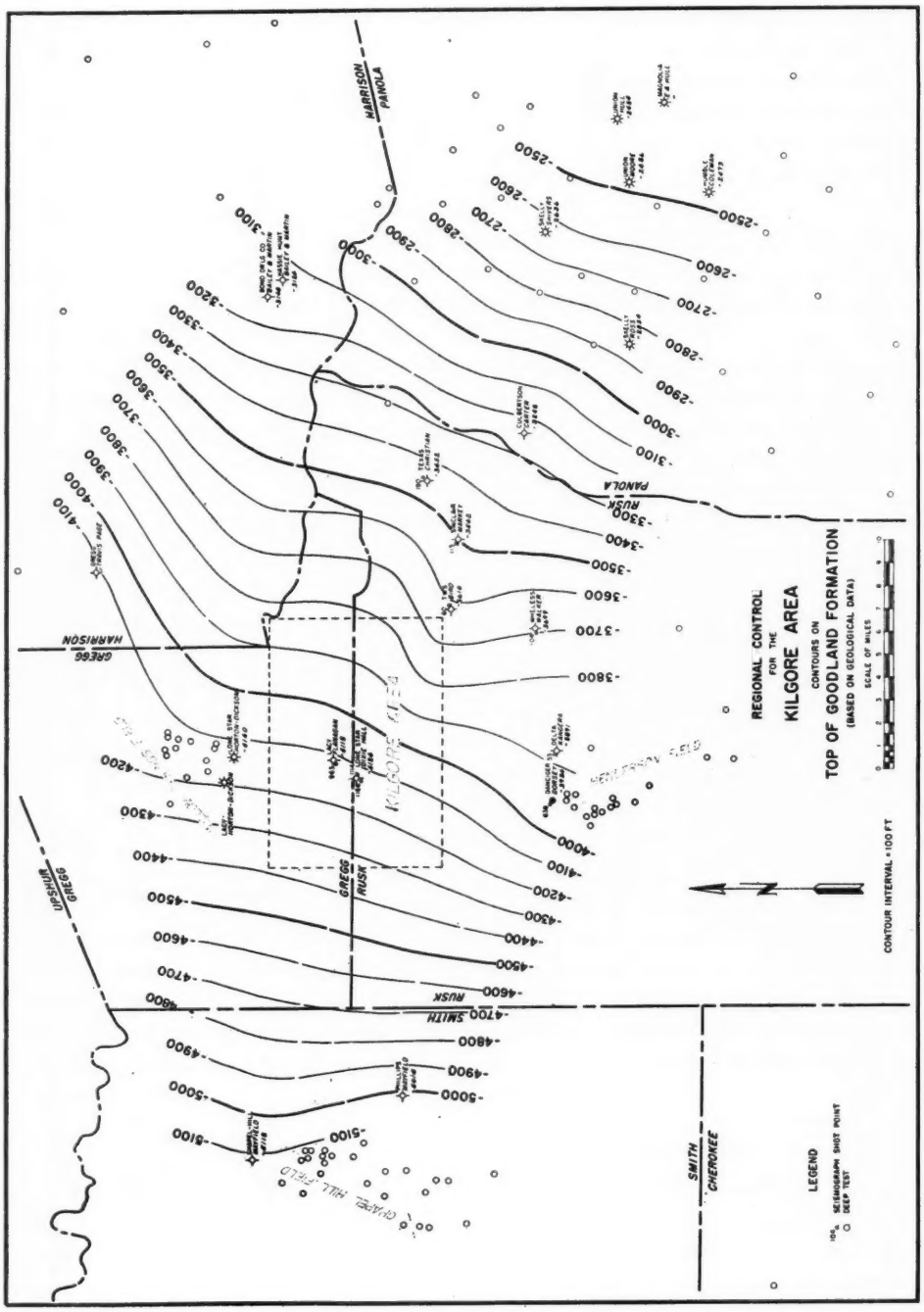

FIG. 4. Regional Control for Top of Goodland Formation

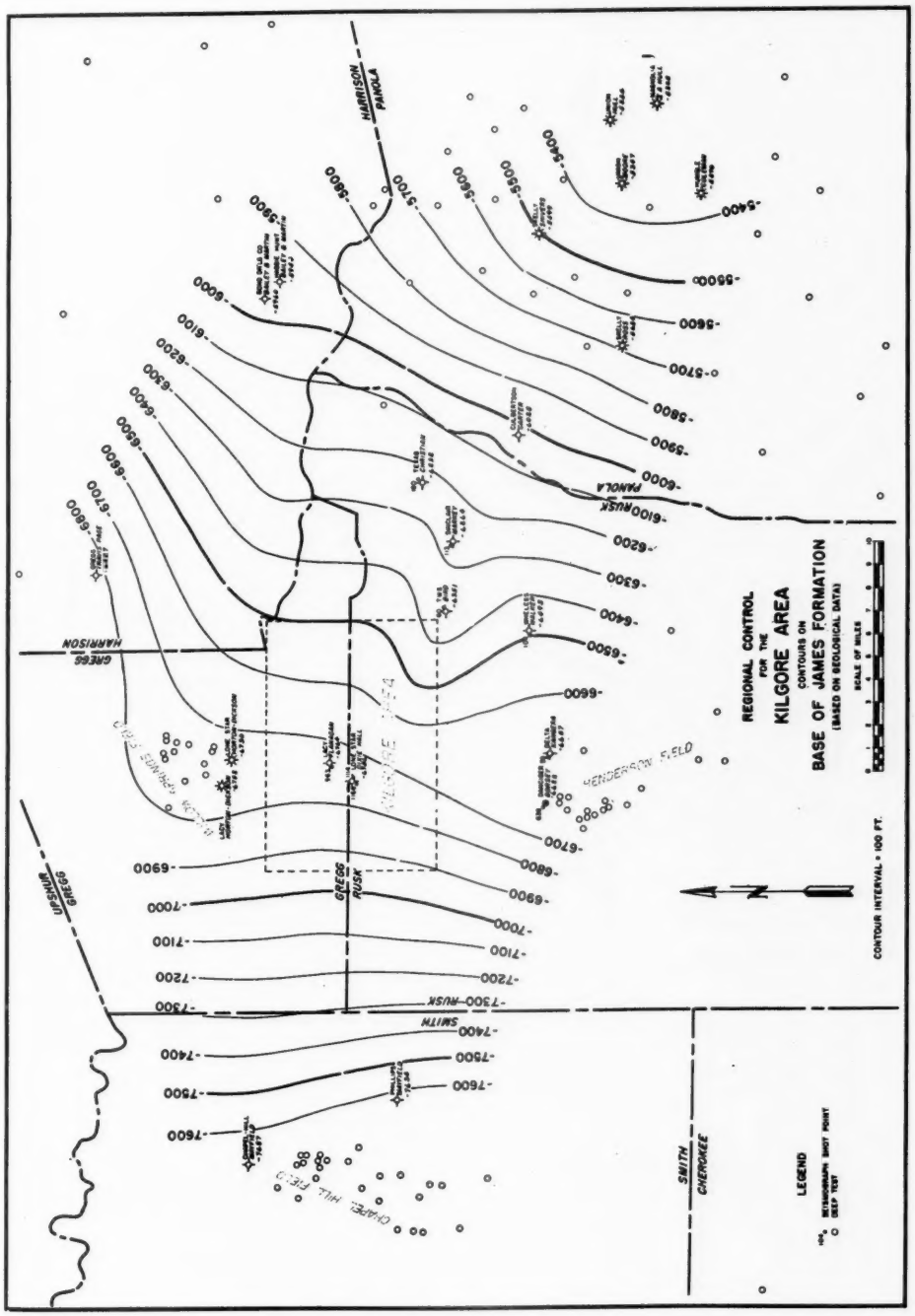

FIG. 5. Regional Control for Base of James Formation

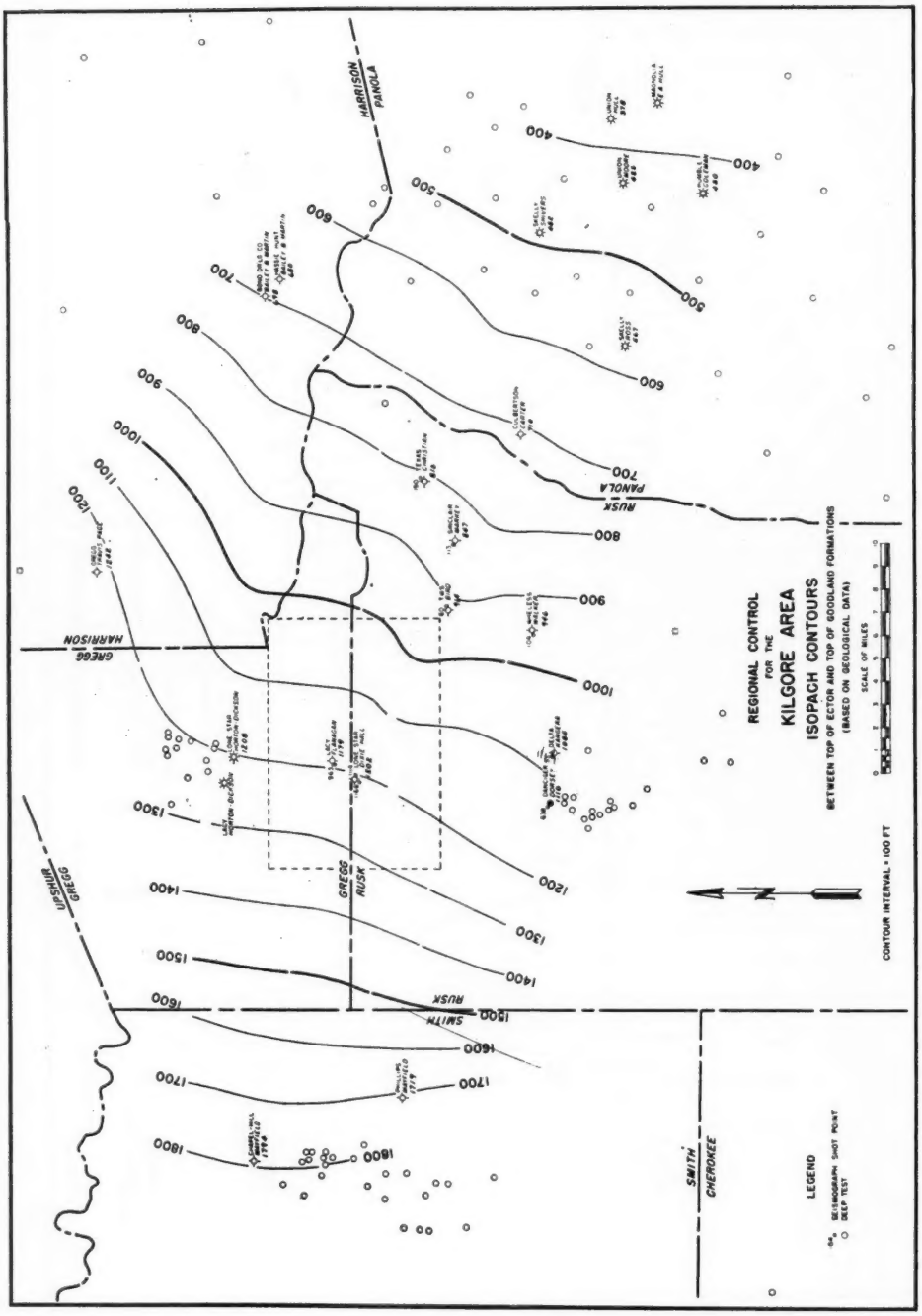

FIG. 6. Regional Control, Isopach of Ector to Goodland

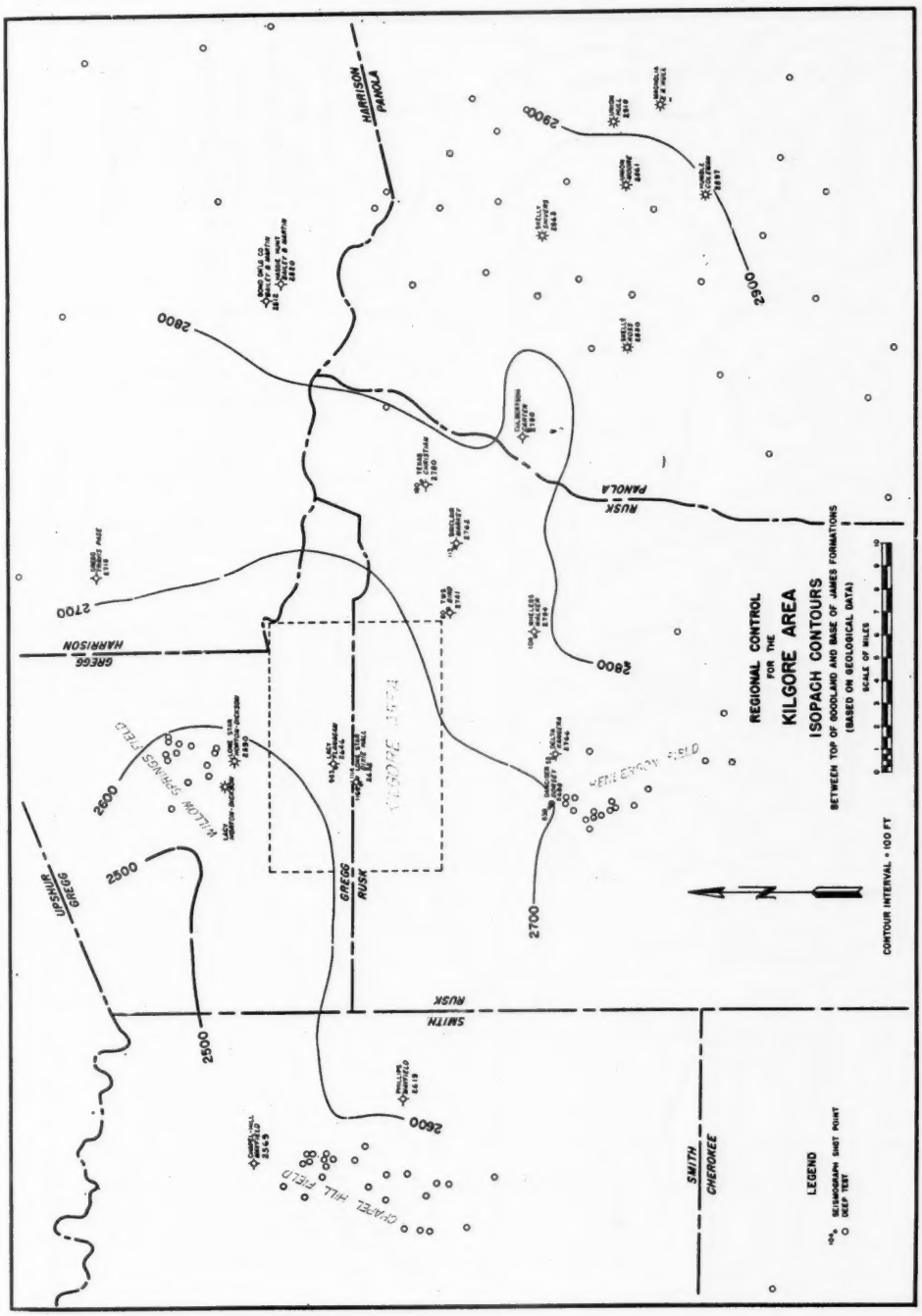

FIG. 7. Regional Control, Isopach of Goodland to James

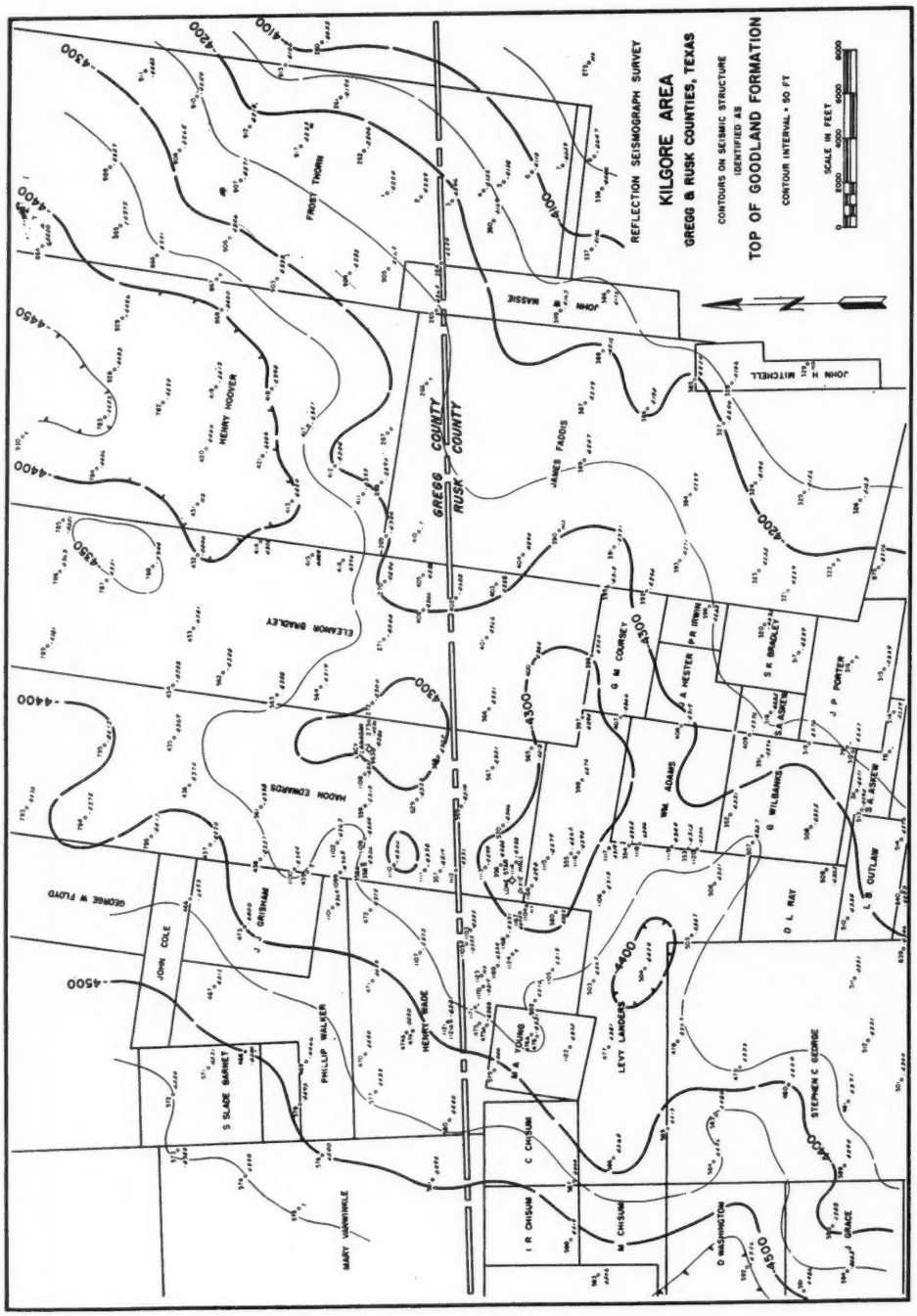

FIG. 8. Seismic Interpretation, Top of Goodland Formation

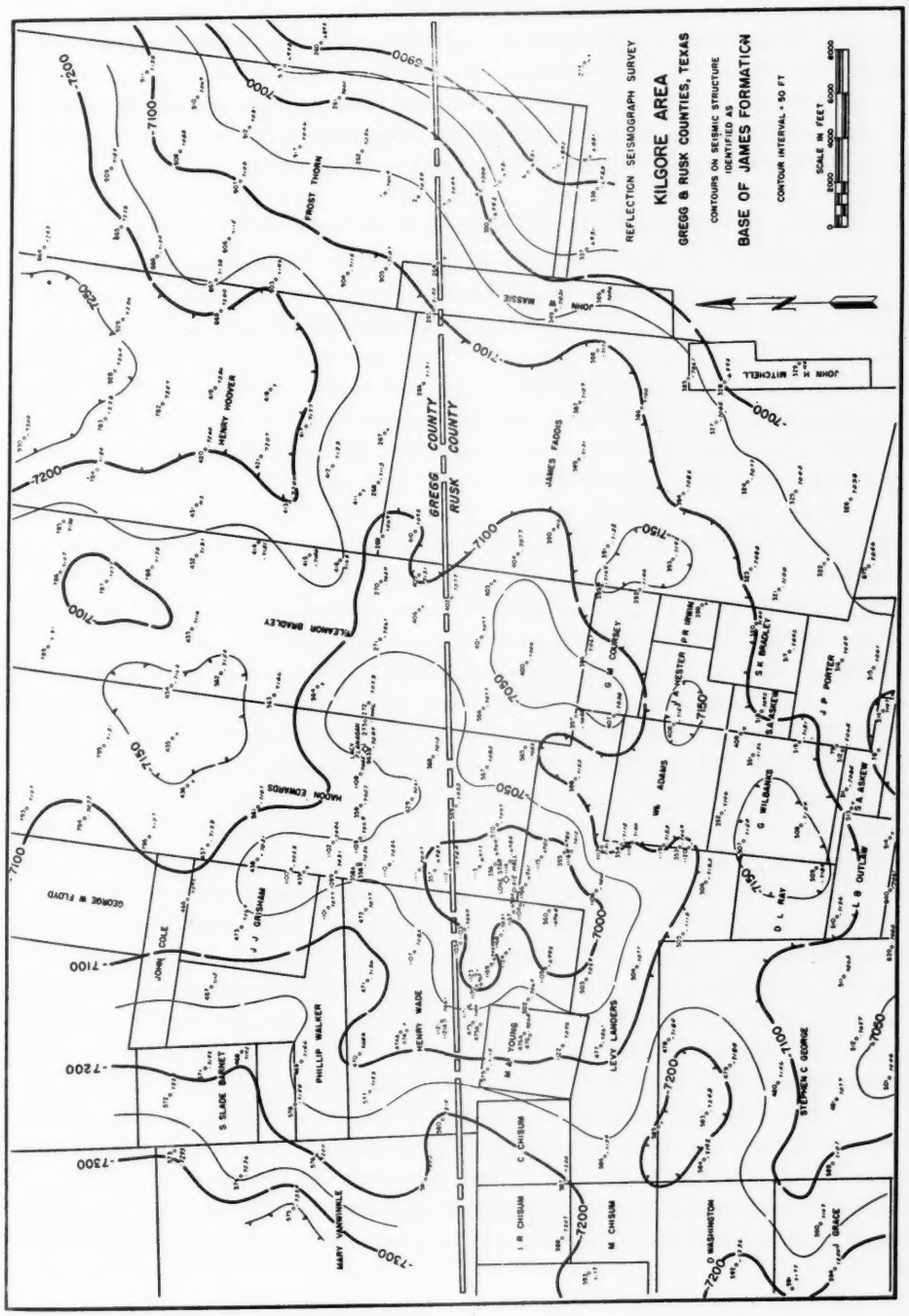

FIG. 9. Seismic Interpretation, Base of James Formation

Petroleum Company No. 1 E. A. Hull well, Panola County, Texas (see Fig. 2), was used to determine the depths to reflecting horizons below this reference plane.

A structural anomaly is revealed on both horizons centering about the southern portion of the Hadon Edwards Survey. The structural closure is approximately 50 feet for the Goodland and 120 feet for the James formation.

AN ANALYSIS TO DETERMINE WHAT IS RELIABLE

The geological interpretation has both good and bad features. On the favorable side are the vast amounts of published geological information that may be combined with the accurate data of electrical logs and sample study to provide a satisfactory regional interpretation.

To the discredit of the geological picture must be listed the lack of sufficient data. The density and distribution of data in this area are such that anticlinal features covering an area as large as fifty square miles may be completely hidden in the areas of no data between wells.

A proper evaluation of the seismic interpretation must include an examination of the validity of the velocity assumptions that were applied to convert times to depths.

A sub-weathering velocity of 8,000 feet per second was used to refer all reflection arrival times to an assumed equivelocity surface at an elevation 200 feet above sea level. To check this assumption, uphole studies of the reflection profiles in the neighborhood of the Hadon Edwards Survey were prepared. Utilizing brief and insufficient data, this investigation led to the conclusion that a lower sub-weathering velocity of 6,500 feet per second might be more applicable in some areas. An independent check on this computation was obtained from the vicinity of the Texas No. 1 Christian well. Results of good data give a sub-weathering velocity of 6,000 feet per second. It can then be concluded that there are local areas which have a sub-weathering velocity significantly lower than the 8,000 feet per second which was used. If the sub-weathering velocity is the same for all portions of the area, the error introduced is of serious consequence only when the topography is marked by frequent and abrupt elevation changes. There are portions of the Kilgore Area that have a relief of 100 feet in a distance of 1,000 feet. An error in sub-weathering velocity of the above magnitude would cause a false structural relief of 45 to 50 feet in this distance. On the other hand, if the sub-weathering velocity varies locally, the error introduced assuming a constant velocity can be even more perplexing. In the Kilgore Area the surface formations are relatively flat lying, but the surface topography is rough; therefore, the same formations are not always encountered in the same thickness. To assume that different formations will have the same velocity is an error of serious nature.

The solution to this difficulty is to maintain a close check of the sub-weathering velocity by deep uphole surveys placed at strategic intervals within the area

surveyed. These direct determinations will almost completely eliminate errors from this source. In the Kilgore Area these measurements were not made; thus no data are available on which to base corrections of the original seismic interpretation.

The time-depth function used in the computation of all seismic data was based on a velocity determination in the Magnolia Petroleum Company No. 1 E. A. Hull well, Panola County, Texas. The relationship of this well to the Kilgore Area is shown on Figures 2 through 7. The original interpretation was based on the assumption that there is no regional velocity gradient in this area. This assumption has been checked by comparison with a velocity determination in the Texas No. 1 Christian well (Fig. 2) and by correlation of well data and adjacent seismic reflection profiles (utilizing the Magnoila-Hull velocity determination at locations indicated on Figure 3). It would appear to be a fallacious assumption to expect the velocity to remain the same in areas which have different sections beneath a marked unconformity; but, in both checks, the assumption of no significant regional velocity gradient appears to be substantially correct.

In an area like the Gulf Coast where velocity increase with depth follows a fairly predictable pattern, a comparison such as this induces a complacency regarding velocity variation. In areas that do not conform to the established pattern, errors in interpretation of serious nature may result. For the same reason, an area of this type can be the best illustration that an integration of geological data with the geophysical assumptions is absolutely necessary.

In the Kilgore Area, although no large regional velocity gradient appears to exist, there remains the possibility of local velocity variations which may materially affect the seismic results. This possibility is very apparent on the East-West Cross-Section (Fig. 2), and on Figure 10, a paleogeological interpretation of the surface immediately preceding Austin time, where the truncation of Washita formations occur at the base of the Ector chalk. The beds of the Washita group are of different lithologies and, thus, may be expected to possess different velocity characteristics. Does not the successive truncation of these formations produce exactly the same effect as lateral changes in lithology? This is the most elusive problem of a seismic interpreter. Where lateral variations of lithology occur, velocity is also usually affected, and the conversion of time to depth assuming a uniform velocity function is erroneous. However, if forewarning is given to the geophysicist, the seismic interpretation may be qualified to allow a better evaluation of geologic structure.

A brief summary of this analysis is necessary to emphasize the fact that if the geologist and geophysicist pool their resources a better interpretation will be possible. In the Kilgore Area the points to be emphasized are: (1) the geological interpretation is based on accurate data, but the density of the data leaves much to be desired; (2) the velocity assumptions of the seismic interpretation may be in error in two specific instances: (a) the sub-weathering velocity may be too high

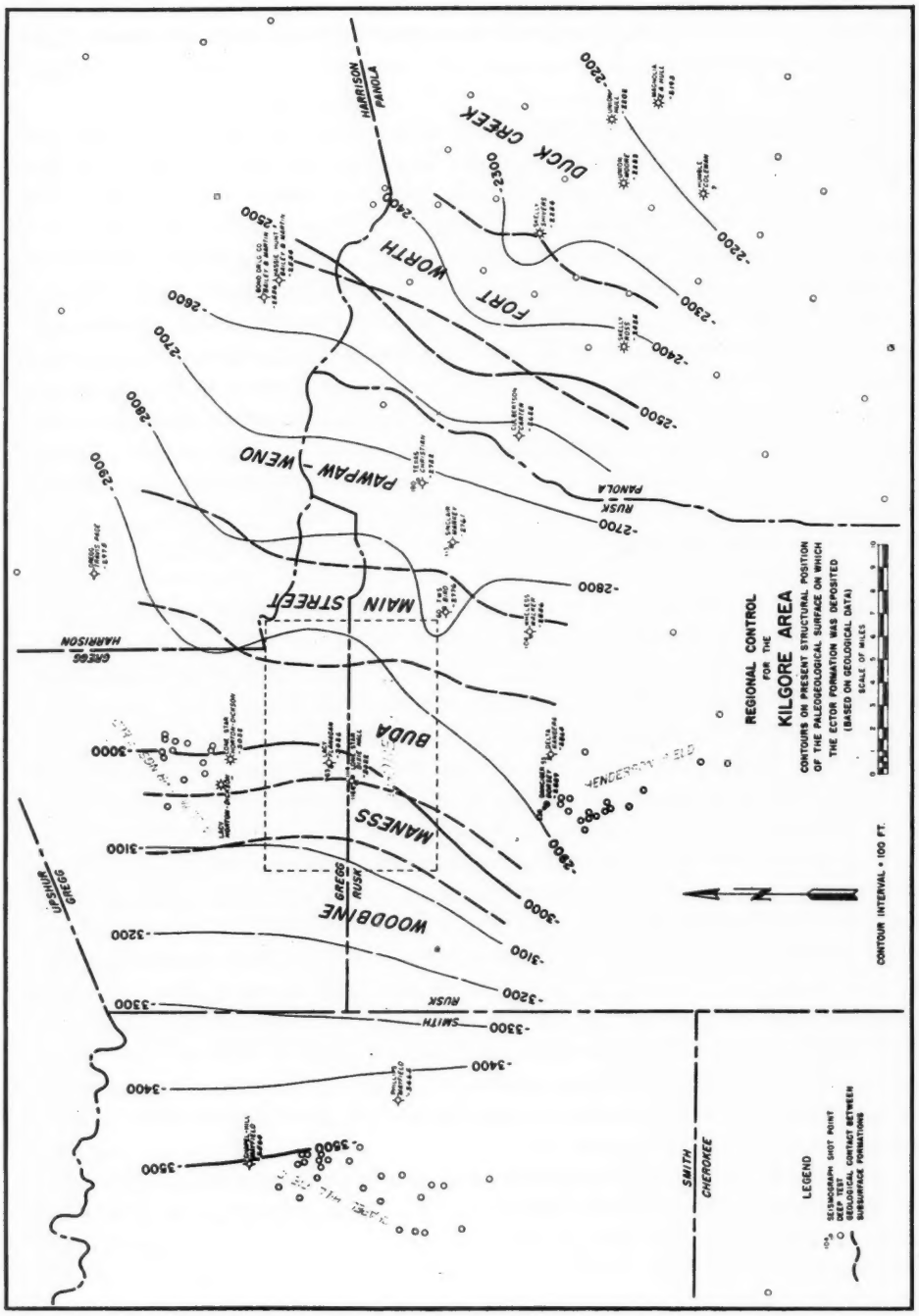

FIG. 10. Present Structural Position of the Paleogeological surface on which the Ector Formation was Deposited

or not uniform, thus giving over or under exaggerated structural anomalies in areas of rough topography; (b) even though there is no evidence of a large scale regional velocity variation; critical examination of the geology points to the possibility of local velocity variations which, without computations to eliminate them, can materially affect the seismic interpretation.

It is now convenient to repeat the purpose of this paper and apply the reasoning specifically to the Kilgore Area. There is a vital need for cooperation between geologist and geophysicist in order to eliminate erroneous interpretations of geologic structure and obtain instead an accurate evaluation on which exploration programs can be based. In the Kilgore Area there are available accurate geological data lacking in density. There are available seismic data of sufficient density, but lacking in accuracy, perhaps due to erroneous assumptions which were used in converting time to depth. Should it not be possible to take what is valid from each set of data, and combine to obtain a more reliable interpretation of the subsurface structure?

AN INTEGRATION OF THE DATA

The questionable character of the sub-weathering velocity is to be deplored; but, because no valid data exist to make such a correction, no useful purpose of this discussion can be served by attempting it. It was a geophysical error which could have been corrected by geophysical methods.

Correction for the effect of local velocity variation is simple in principle but difficult in application, because no data are available on the interval velocities of the formations truncated within the Kilgore Area. The formations involved are the Maness shale, the Buda limestone, and the Main Street marl and limestone. The Grayson marl is omitted because its presence is questionable.

The nearest available velocity determinations which penetrated these formations are almost forty miles away; hence measurement of interval velocity in these wells can give only a general idea of the velocity to expect. In addition, most of the surveys measured interval velocities of several formations as a unit; thus no useful information can be gained from them for this problem. On the basis of incomplete data which has not been released for publication, only general assumptions of interval velocities for these formations can be made. Thus, we can make no technically certain interpretation without a velocity determination in the area.

For the purposes of this discussion arbitrary values of a reasonable nature shall be assigned to each formation. In this way, a possible effect of the truncation of beds at the unconformity may be demonstrated. An accurate interpretation will have to be based on a velocity determination in the Kilgore Area. This is the problem of the oil industry.

The Maness formation is the bronze shale of the East Texas Field (Bailey, 1945). A velocity of 9,000 feet per second shall be assigned to it. This is the characteristic velocity of shale at this depth (Navarte, 1946).

The Buda formation is a dense limestone (Bailey, 1945). A velocity of 15,000 feet per second is assigned to it. This value was arrived at through careful studies

of the interval velocities of dense limestones throughout the East Texas Basin. The value may be slightly high, but it is not enough in error to invalidate the results of this calculation.[1]

The Main Street formation is a marl and limestone (Bailey, 1945). An interval velocity of 11,000 feet per second is assumed as a conservative value for this formation. A higher velocity would have the same effect and would increase the correction to be applied to seismic depths.

The instantaneous velocity (V_i), which is shown on Figure 11 below the Main Street formation, is the computed or expected velocity at the depth of the unconformity. Actually, another high velocity bed may lie beneath the Main Street; but, if one does, the only effect would be to subtract a constant additional time increment from travel times to reflecting horizons below this zone. In any case, the addition of material having a velocity in excess of the normal velocity at that depth would cause a depth distortion.

These arbitrarily assigned velocity values are undoubtedly in error but are based on comparison of many data and probably are approximately correct in their relative relationship. Examination of the effect of truncation of high velocity beds may be accomplished by a simple analysis. As a matter of convenience, this analysis will also serve to demonstrate the effect of a similar correction of the original seismic interpretation.

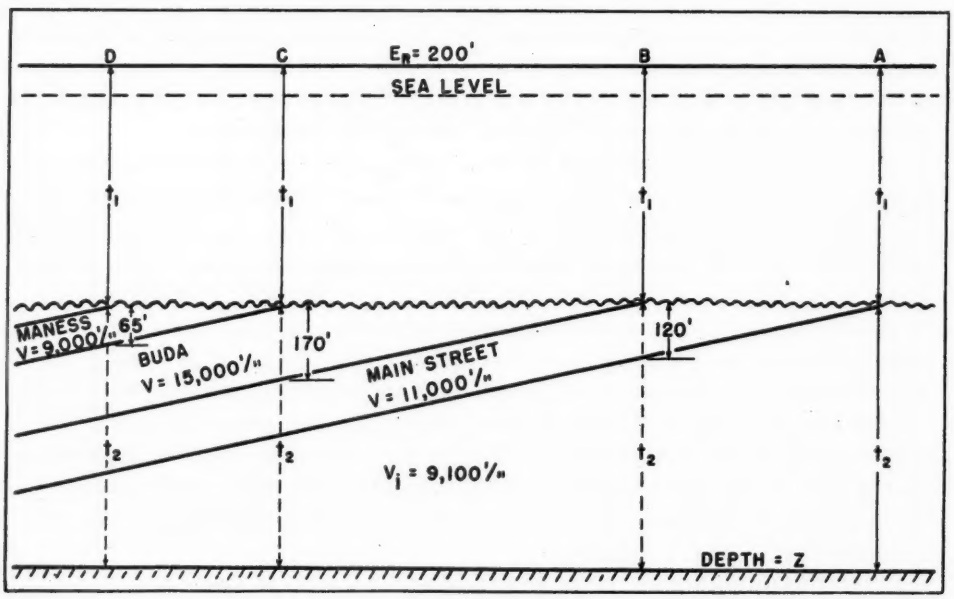

FIG. 11. Velocity Assumptions for Formations Truncated at the Unconformity

[1] Velocities for dense limestones in the East Texas Basin range from 14,000 to 16,000 feet per second. A direct measurement of interval velocity in the Buda at a location 40 miles away from the Kilgore Area gave a velocity of 15,000 feet per second.

In Figure 11, the two-way travel time to a depth Z at point A may be expressed

$$T_{ta} = 2(t_1 + t_2).$$

At point B to the same depth the time is

$$T_{tb} = 2\left[t_1 + t_2 - \frac{120}{9,100} + \frac{120}{11,000}\right].$$

The time shortening caused by the Main Street high velocity layer is

$$T_{ta} - T_{tb} = 2\left[-\frac{120}{11,000} + \frac{120}{9,100}\right] = .004 \text{ seconds.}$$

In a similar manner at point C the time shortening due to the combined effect of the Buda and Main Street formations is

$$T_{ta} - T_{tc} = -2\left[-\frac{120}{9,100} - \frac{170}{9,100} + \frac{120}{11,000} + \frac{150}{15,000}\right] = .020 \text{ seconds.}$$

At point D the total shortening remains the same as beneath point C.

$$T_{ta} - T_{td} = -2\left[-\frac{190}{9,100} - \frac{170}{9,100} - \frac{65}{9,100} + \frac{120}{11,000} + \frac{170}{15,000} + \frac{65}{9,000}\right]$$
$$= .020 \text{ seconds.}$$

Using the instantaneous velocity applicable to their depth, for the Goodland formation this correction is 6 feet for each .001 of a second; for the James formation this correction is 7.5 feet for each .001 of a second. These computations are the basis for the correction contours shown on Figures 12 and 13. The positions of contours were determined from the paleogeological surface (Fig. 8), and therefore represent an integration of geological data to make a basis for a physical depth correction.

Figures 14 and 15 show the seismic interpretations after the application of these corrections. The structural closure of the Goodland formation (Fig. 14) is almost negligible in the area of the Hadon Edwards Survey. The interpretation of the James formation shows that critical structural closure on the east side of the anomaly has been greatly reduced from an indicated 120 feet in the original interpretation to not more than 60 feet. Without more certain geological evidence, this interpretation was made on the assumption that the truncation of the Buda limestone is uniform. Abrupt truncation would provide an additional distortion. If such is the case, the closure would be even further reduced if proper corrections were made. Thus, a critical appraisal leads to the conclusion that the structural closure indicated by the seismic data may be in part unreliable. Coupled with the doubtful validity of the sub-weathering velocity assumption, the original seismic interpretation almost certainly is in error. The interpretation

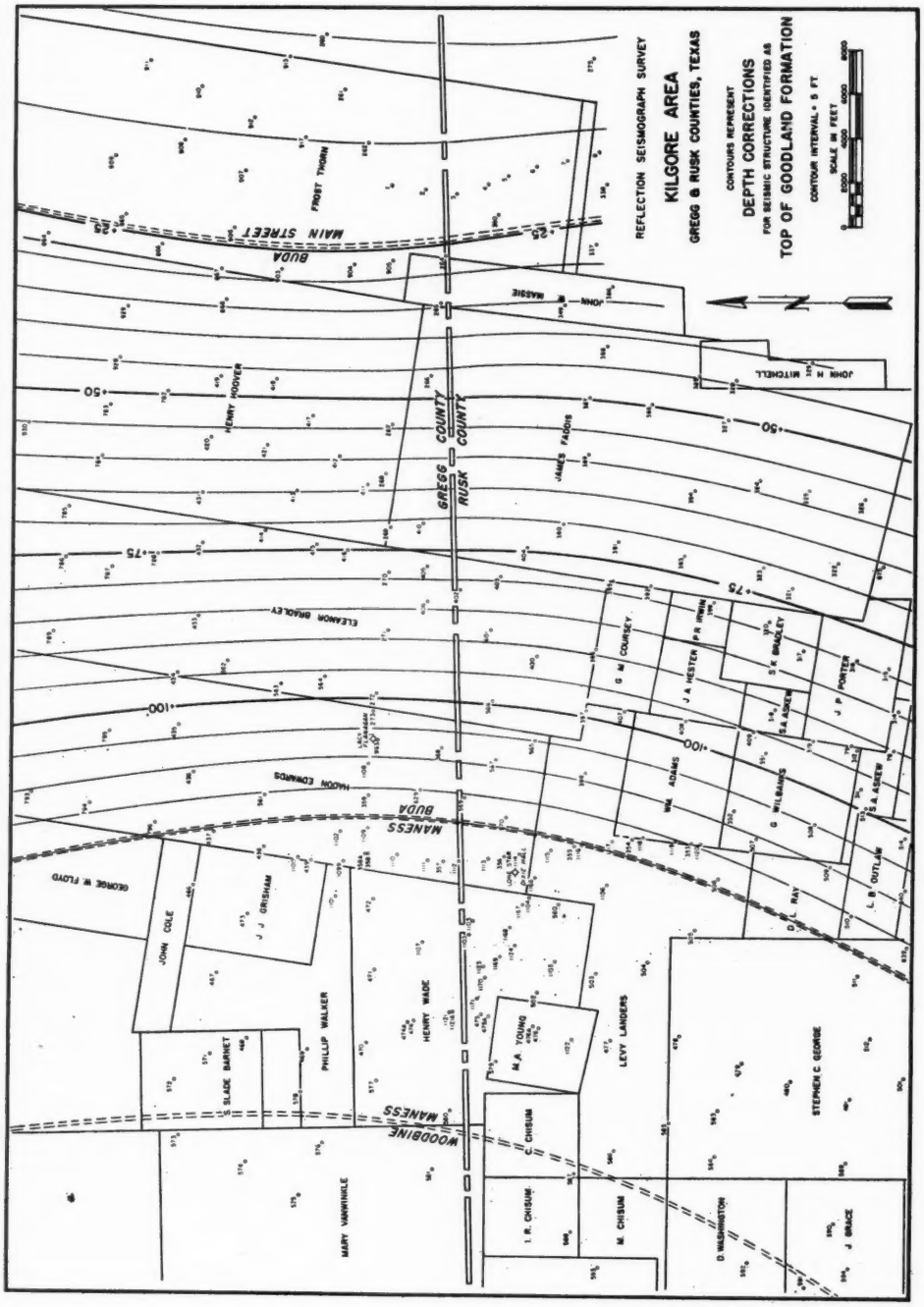

FIG. 12. Depth Corrections, Top of Goodland Formation

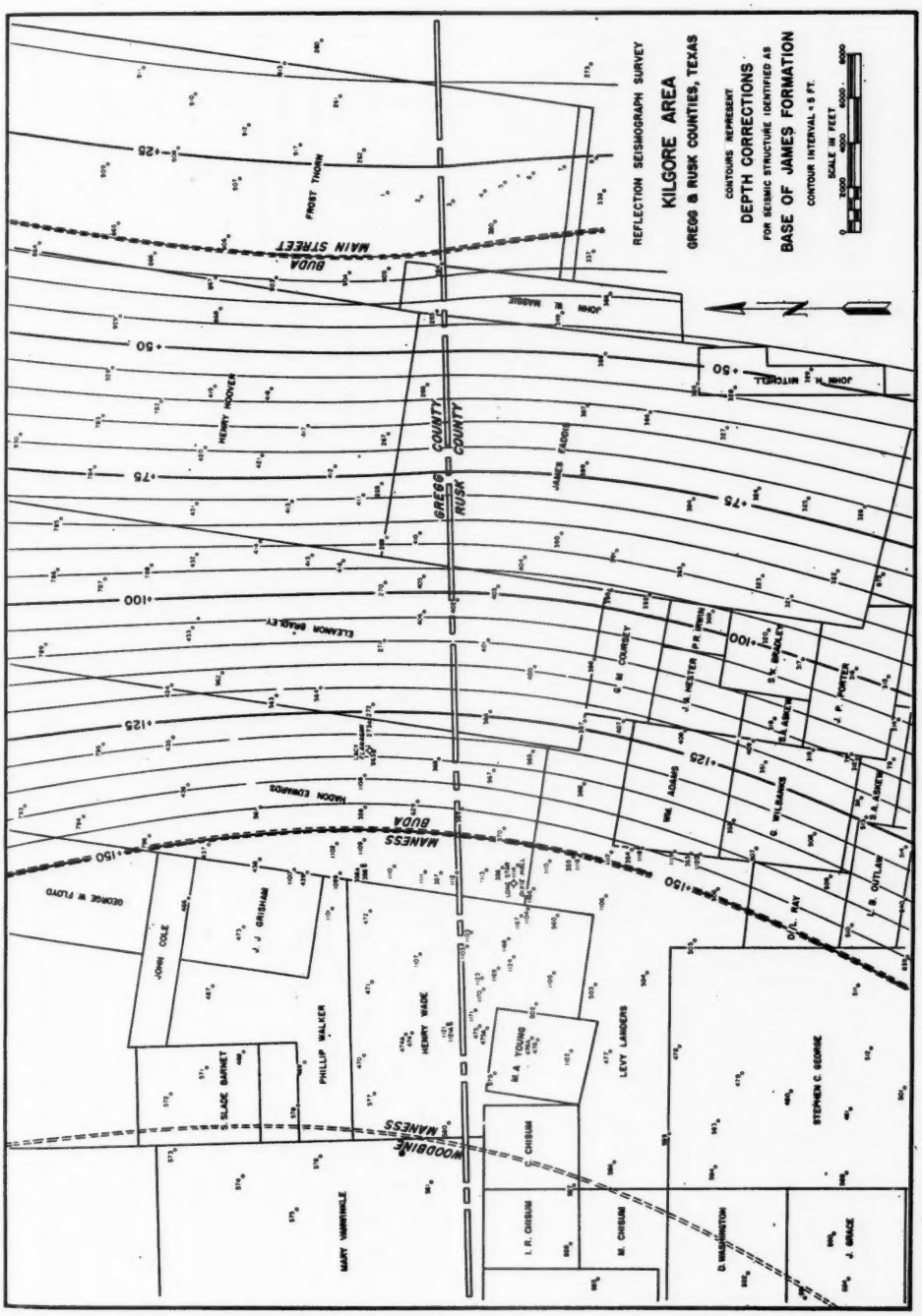

FIG. 13. Depth Corrections, Base of James Formation

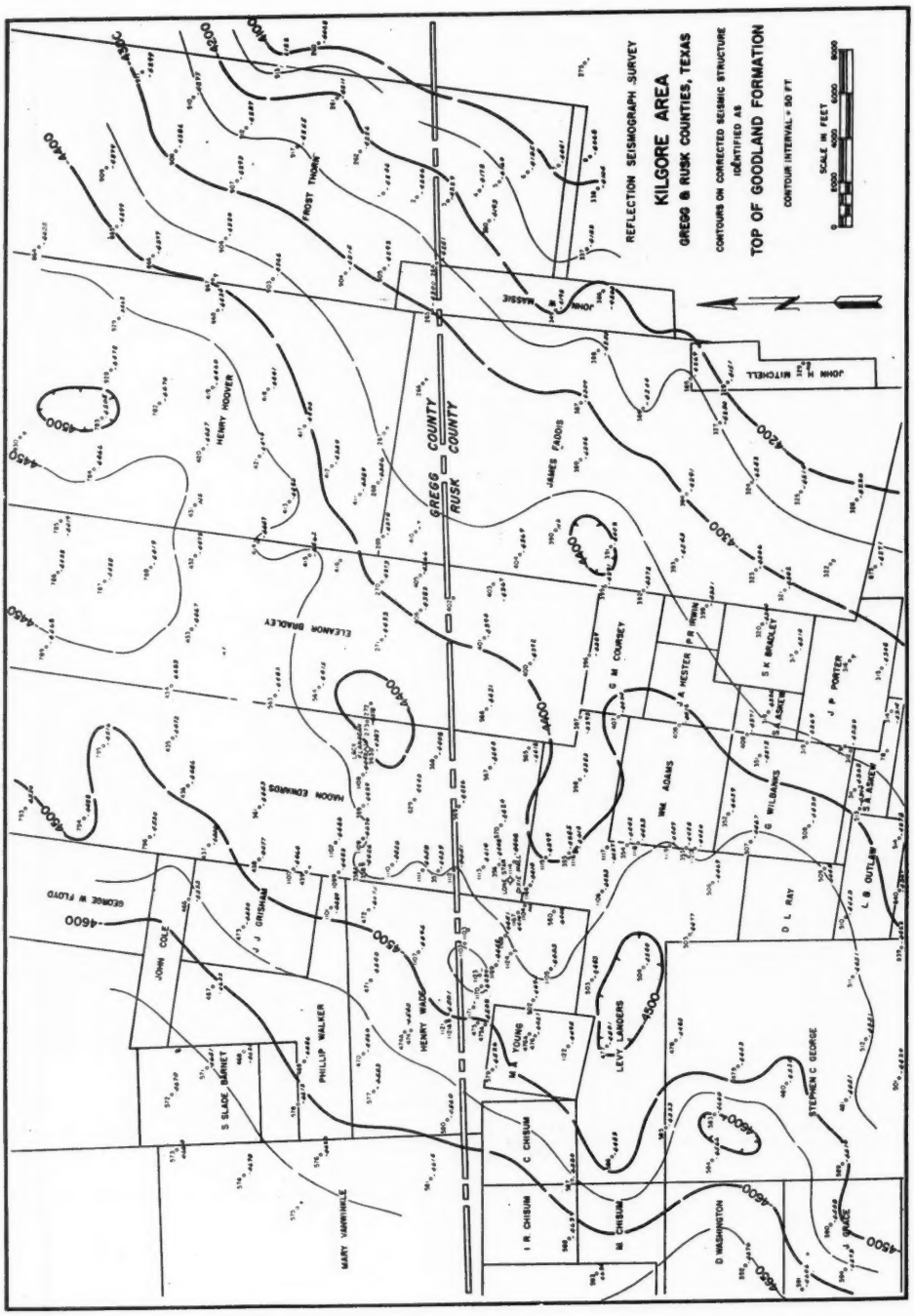

FIG. 14. Corrected Seismic Interpretation, Top of Goodland Formation

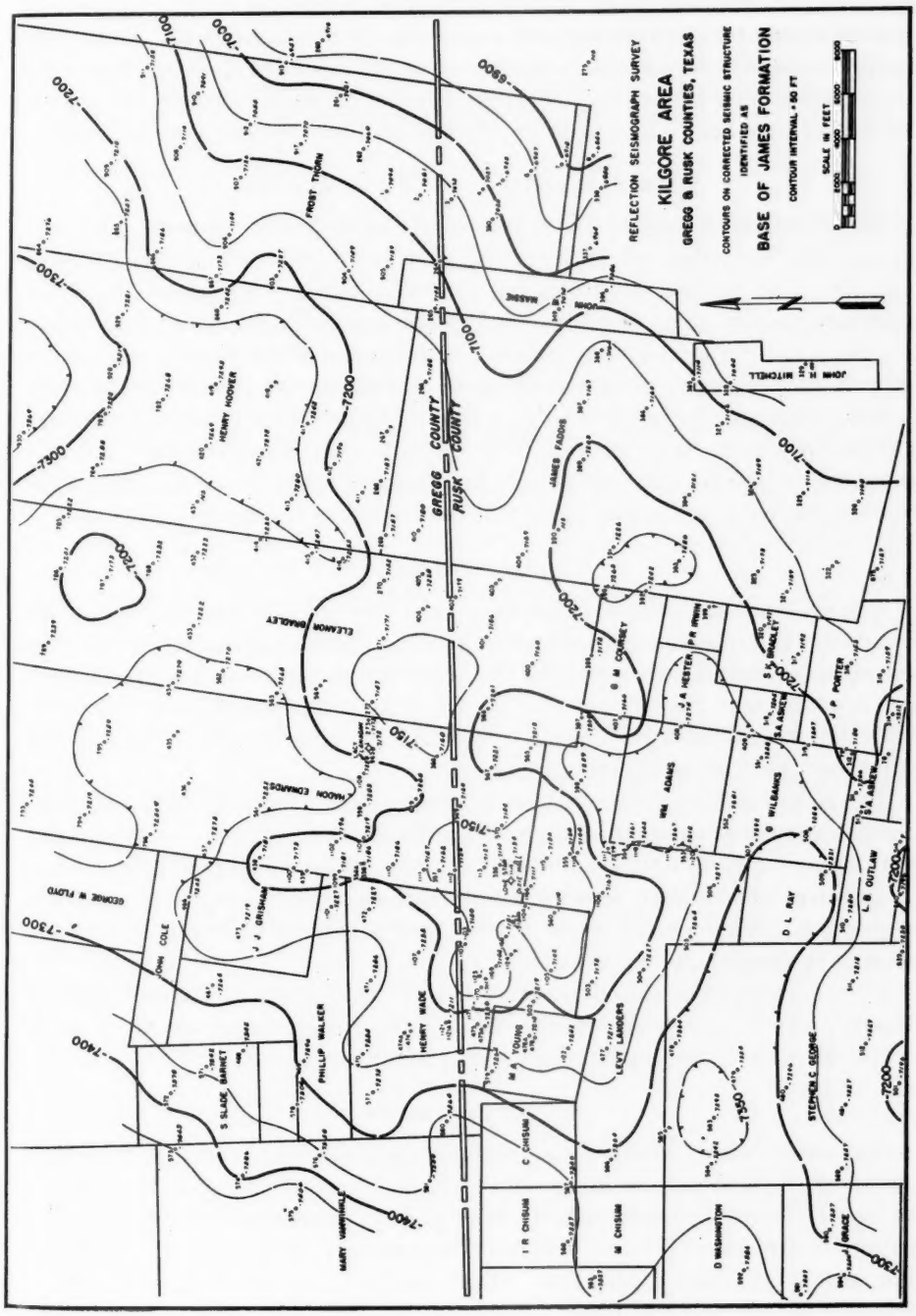

FIG. 15. Corrected Seismic Interpretation, Base of James Formation

presented here has been based on assumed values of interval velocities in formations truncated by the unconformity at the base of the Ector chalk. This latter interpretation is believed to represent a step in the right direction but in no case can be relied upon for accurate representation of geologic structure; because it also suffers from the lack of sufficient data to properly convert time to depth.

A FURTHER APPLICATION OF THE METHOD

This thesis of geological and geophysical coordination has been concerned chiefly with the effect of stratigraphic and lithologic variations on seismic velocities. The method of eliminating the effect of these variations indirectly illustrates another great possibility of expansion for the reflection seismograph into the search for stratigraphic traps of many types. If the geological evidence can present a relatively good average surface at depth. the seismic irregularities for this depth may be interpreted in terms of the predicted change in lithology or pinchout pattern of formations in the upper section. The shale and limestone truncations of the Washita group could have been localized by working backward from the seismic irregularities present at the top of the Goodland formation.

CONCLUSIONS

The exploration methods which have been and are standard practice in the oil industry often produce incorrect results. This illustration has shown that the limitations of the geologic and reflection seismograph exploration methods are of such a nature that they do not overlap. Of greater importance, it is possible to utilize the maximum interpretation of geological data as a guide to the velocity variations which affect the seismic interpretation.

The lack of sufficient velocity information can be a serious handicap to correct interpretation of geologic structure by the reflection seismograph. For this reason, every opportunity to obtain additional velocity information should be utilized: (1) sufficient near-surface velocity determinations should be made to eliminate errors from this source, (2) every outpost well should be surveyed for velocity before it is plugged and abandoned.

It is evident from this illustration that existing seismic interpretations of structure that are in disagreement with known geologic data may often be recomputed for a correct interpretation at a small extra cost.

ACKNOWLEDGMENTS

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GEOPHYSICAL EXPLORATION IN THE SAN JUAN BASIN*

NEAL CLAYTON†

ABSTRACT

Geophysical surveying in the San Juan Basin involves a number of problems peculiar to the area. Magnetometer and gravity meter surveys are complicated by topography and the presence of Tertiary intrusives. Scarcity of water is a major problem for seismic crews. Some arrangements must be made for housing crew employees. Velocity and subsurface control are extremely limited.

The San Juan Basin, one of the areas currently being actively explored by geophysical methods, is located in the so-called Four Corners area of Utah, Colorado, New Mexico, and Arizona. Most of the Basin lies in northwestern New Mexico, and includes all or part of the following counties: San Juan, Rio Arriba, Sandoval, and McKinley. In the north it extends into Montezuma, La Plata, and Archuleta Counties in Colorado. Structurally, the limits of the Basin are clearly defined by the La Plata and San Juan Mountains to the north, the Nacimiento Mountains to the east, the Zuni Mountains and the Mount Taylor volcanic field to the south, and the Defiance Uplift to the west (Fig. 1). The lowland area thus enclosed covers some 15,000 to 20,000 square miles and includes the smaller Acoma, Chama, and Zuni embayments.

Some geophysical exploration has been carried on in the San Juan Basin for over twenty years. The first oil discovery in New Mexico took place in McKinley County in 1911. Since that time activity has suffered several periods of stagnation due primarily to unfavorable marketing and transportation conditions. The recent increased demand for petroleum products and the permit granted the El Paso Natural Gas Company last year to build a 24-inch pipeline to the West Coast have stepped up exploration considerably.

As compared with last year, geophysical activity in the Basin this year has shown a marked increase. Between January and November of last year, 202 crew-weeks of activity were reported in the Basin. From November of last year to October of this year, a total of 362 crew-weeks was reported—a considerable increase. These figures are for all types of geophysical activity. At present there are seven seismic and two gravity crews at work in the San Juan Basin.

Geologically speaking, the San Juan is an asymmetrical basin with steep dips around its northern and eastern margins, and gentler dips to the south and west. The rocks exposed in and around the Basin range in age from Pre-Cambrian to Tertiary. In general, the older rocks are exposed along the outer edges of the Basin, being faulted and upturned against the positive areas. In

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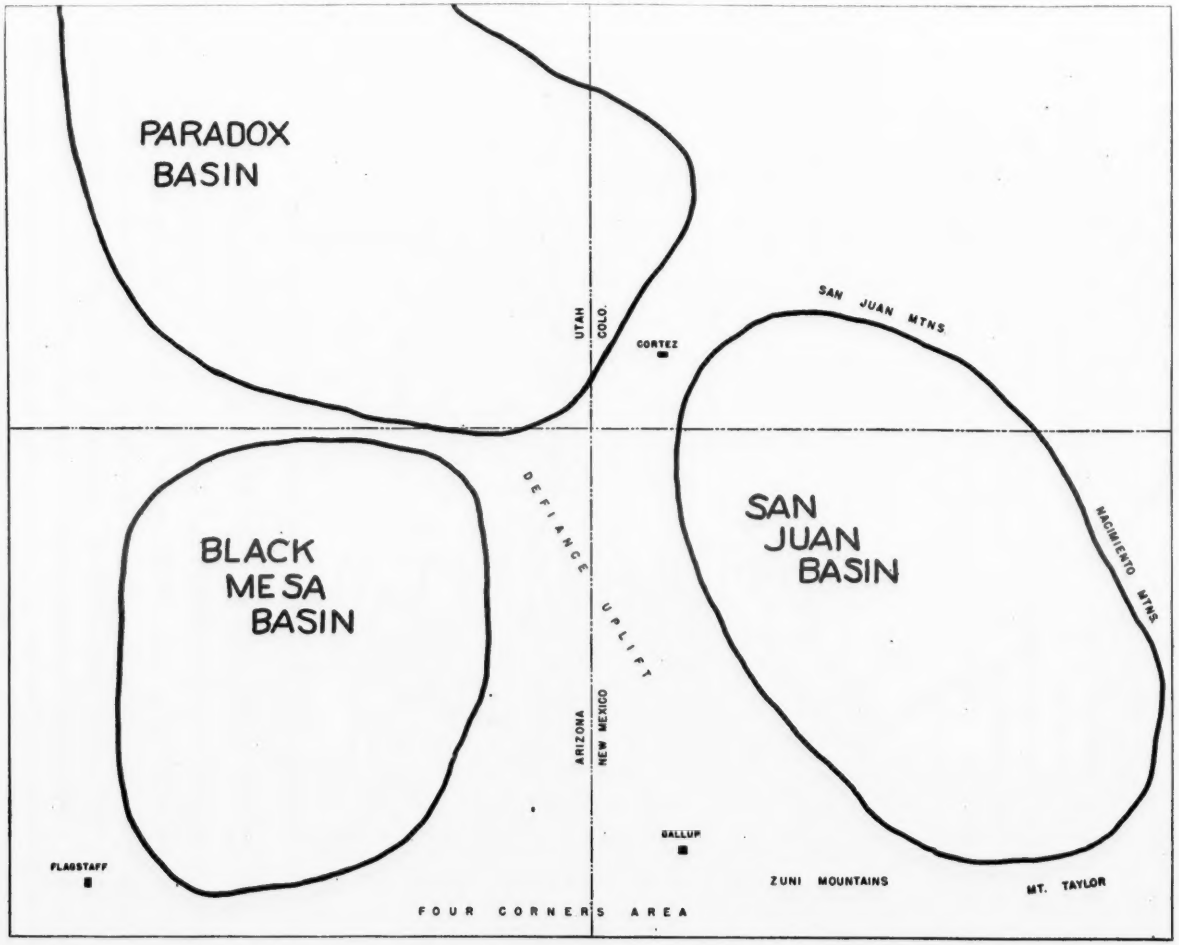

FIG. 1. Location of San Juan Basin with respect to the Black Mesa and Paradox Basins.

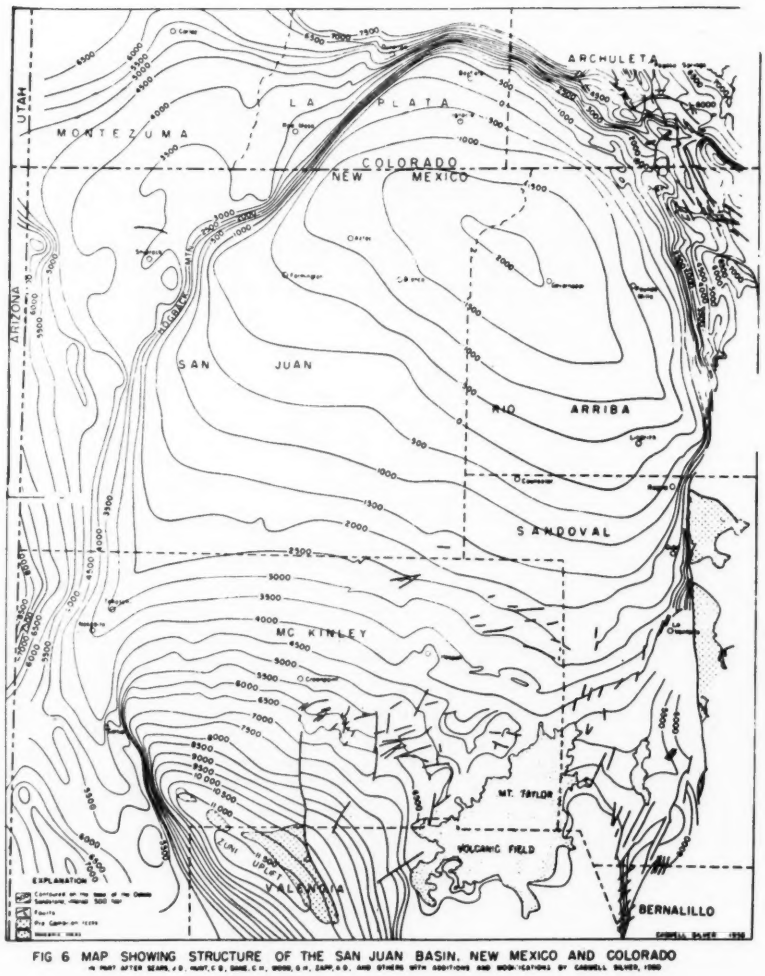

FIG. 2. Structural contour map on base of Dakota Sandstone (Courtesy of Caswell Silver).

its deepest part it is believed that the Basin has in excess of 15,000 feet of sediments. In some areas, principally around the eastern, southern, and western margins, volcanic plugs, dikes, and lava flows are prominent features. Except for the lava flows, these late Tertiary volcanic features have little effect on geophysical exploration. A regional contour map of the base of the Dakota sandstone of Lower Cretaceous Age indicates the general subsurface pattern within the Basin (Fig. 2). The numerous faults along the eastern and southern margins are noteworthy features. The steep monoclinal flexure along the northwestern margin is reflected at the surface by a prominent "hogback" formed by the Mesa Verde sandstone.

In the past, most gas discoveries in the Basin have been made in stratigraphic

or lithologic traps on monoclines, while oil has been located on domes or anticlines. When it is realized that the density of distribution of deep "wildcats" in the San Juan Basin at present is about equal to that of the Permian Basin twenty-five years ago, the conclusion must be reached that the Basin is relatively unexplored. The presence of possible source beds from the Mississippian to the Tertiary should make this area increasingly important in the future.

Magnetometer and gravity meter surveys in the Basin are influenced by the extreme topographic relief and are hindered by the inaccessibility of certain areas. It was expected that the occurrence of igneous plugs and dikes might influence local gradients. On the contrary, however, according to one operator,

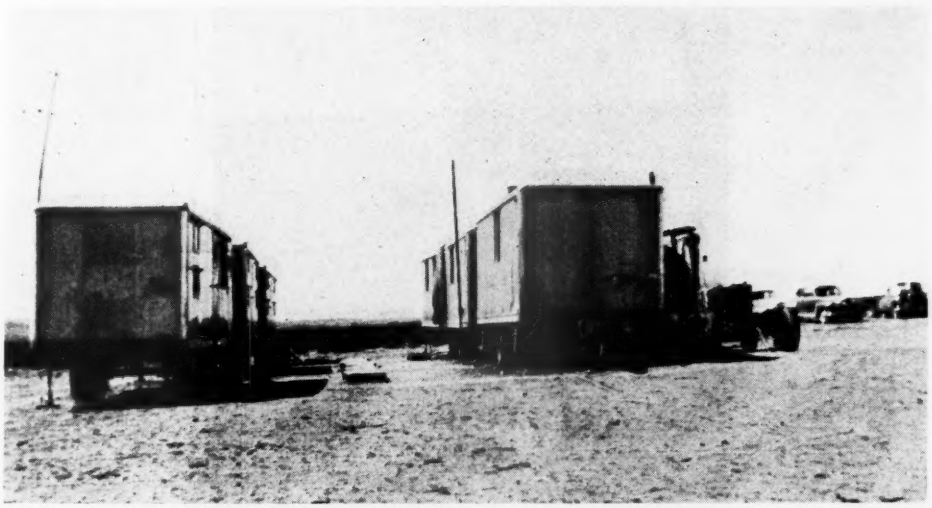

FIG. 3. Trailer camp used for housing of geophysical crew.

it has been found that these features have little effect provided a reconnaissance type survey is employed. This is possibly due to the superficial character of the dikes and the relative dimensions of the plugs. Undoubtedly, with very close detailing, these features would influence the results of magnetic or gravimetric surveys. Lava flows introduce a different problem.

The present acceleration in seismic activity began shortly after World War II. Byrd-Frost and Stanolind were responsible for initiating the boom. A slight lull in activity occurred shortly before the Delhi-Lindrith discovery in 1949. This was the first completely geophysical discovery made in the San Juan Basin. Since a large part of the Basin is covered by Tertiary and other sediments which render impractical the employment of surface geological techniques, the seismograph must here be used to determine subsurface structure. The general belief is that, within the Basin, favorable structures do exist which have no surface expression. Most of the known surface structures are already under lease or have

been tested. The "buried" structures, if present, will be found with the seismograph.

The operating of a seismic crew in the San Juan Basin involves a number of problems peculiar to the area. The first of these is the problem of housing. Aztec and Farmington, the only towns of any size in the Basin, are extremely crowded due to the present drilling activity. In addition, accommodation for transients is very poor. The only solution for efficient operation is a trailer camp (Fig. 3).

Water for drilling and shooting is very scarce. The depth for a water well

FIG. 4. Bulldozer clearing trail for automotive equipment.

varies from 60 to 200 feet in Rio Arriba and Sandoval Counties to over 500 feet in San Juan County. Auxiliary water trucks are a necessity. Air drilling has not been thoroughly tried in the Basin to date.

A large part of the Tertiary cover in the Basin has been heavily eroded and consists of "badlands." Much of the remaining topsoil is either sandy or brush-covered. Consequently, for the efficient movement of automotive equipment, bulldozers are virtually a necessity (Fig. 4). Four wheel drive equipment also is recommended. Flash floods often make the use of 'dozers necessary in order to traverse known trails.

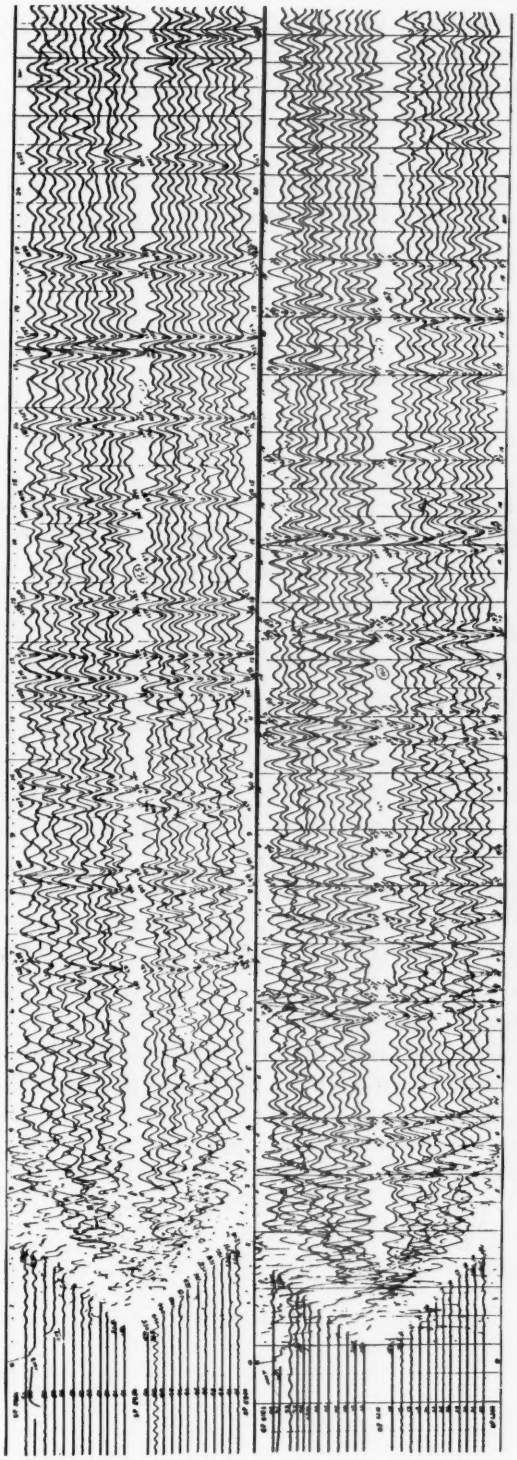

FIG. 5. Seismic records taken in San Juan County, New Mexico.

Shot hole depths generally vary from 80 to 200 feet. In many areas the holes must be "plugged" on the last shot in order to obtain a "clean" record. Charges vary from 20 to 100 pounds. Record quality is generally good, with local exceptions. Reflections are usually obtained from the upper Cretaceous to the Pennsylvanian (Fig. 5).

In those areas where the Pictured Cliffs or Mesa Verde sandstones outcrop, record quality is usually poor to NR. Deepening the holes does not seem to improve the record quality in these areas. Dikes, however, seem to have little or no effect on seismic records.

At the present time, both the continuous and spot correlation methods of shooting are being employed with success. In the former case long "end-on" spreads, although successful in a number of areas, have not been used as generally as straddle spreads.

Possibly the most troublesome problem the geophysicist is called upon to face in the San Juan Basin is that of velocity. This is due to several factors. In the first place very few velocity surveys have been made in the Basin. In some areas the velocity gradient increases into the Basin, while in others the opposite appears to be true. The Tertiary section has a relatively low average velocity, from 9,000 to 9,500 feet per second. Considerable cross-bedding occurs in this part of the section.

Most shales in the Cretaceous section vary from 10,500 to 11,500 feet per second. The Cretaceous sandstone members usually measure 14,000 feet per second. Rapid lateral changes do occur in the Cretaceous section, and these could cause appreciable velocity gradients. It is believed that most of the rapid velocity changes occur above the Jurassic. The interval velocities increase from a value of 12,500 feet per second through the Jurassic section to over 17,000 feet per second through the Pennsylvanian section.

A recommendation is made that velocity surveys be run in all deep wells and that the various operators pool this information so that it will be available. A successful program of seismic exploration cannot be carried out in the San Juan Basin unless adequate velocity data are at hand. All operators must be shown the importance of velocity data.

In conclusion, the author would like to thank the Magnolia Petroleum Company, the Continental Oil Company, and the Skelly Oil Company for their cooperation in making this paper possible.

ORE BODY SIZE DETERMINATION IN ELECTRICAL PROSPECTING*

HAROLD O. SEIGEL†

ABSTRACT

A method of determination of the size of ore body associated with a mineralized intersection is presented which utilizes the primary voltage disturbance created by the body and the variation of the disturbance with electrode spacing. The form of the disturbance function is compared with theoretical curves based on the oblate spheroid.

INTRODUCTION

It is not an uncommon situation that a mineralized intersection of small magnitude is obtained near the end of a long and costly exploratory drill hole. The question that naturally arises is whether this mineralization represents the fringe of a much larger mass of the same or better grade, or is merely a localized deposit, perhaps even a small fissure vein intersected by the hole at a low angle. The fate of further drilling often rests on a relatively arbitrary decision as to what the possibilities of extension actually are.

A very diagnostic physical property which distinguishes metallic sulphide mineralization from the usual country rock is electrical conductivity. A factor of 1,000 fold contrast is not uncommon. Through the use of one of several simple electrodal arrays it is possible to utilize this property contrast towards giving us an estimate of the size of the body associated with an intersection.

BASIS OF METHOD

Figures 1 and 2 illustrate two arrays that may be used for this purpose. The former is simply the "normal array" as used in petroleum electric logging, and the latter may be referred to as the "equispaced three electrode array." Current is passed between C_1, placed a small distance from the intersection, and C_2, placed generally at some convenient surface point at a large distance from C_1. The current may be dc, commutated dc, or very low frequency ac. The resultant voltages in the ground are measured between P_1, placed on the opposite side of the intersection from C_1, and an equal distance therefrom, and P_2, placed in figure 1 at a large distance from all the other electrodes and in figure 2 at a distance below P_1 equal to C_1P_1.

The flow pattern and potential distribution will be altered by the presence of the mineralization from what it would normally be in barren rock. Current

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† Newmont Exploration, Ltd., Jerome, Arizona.

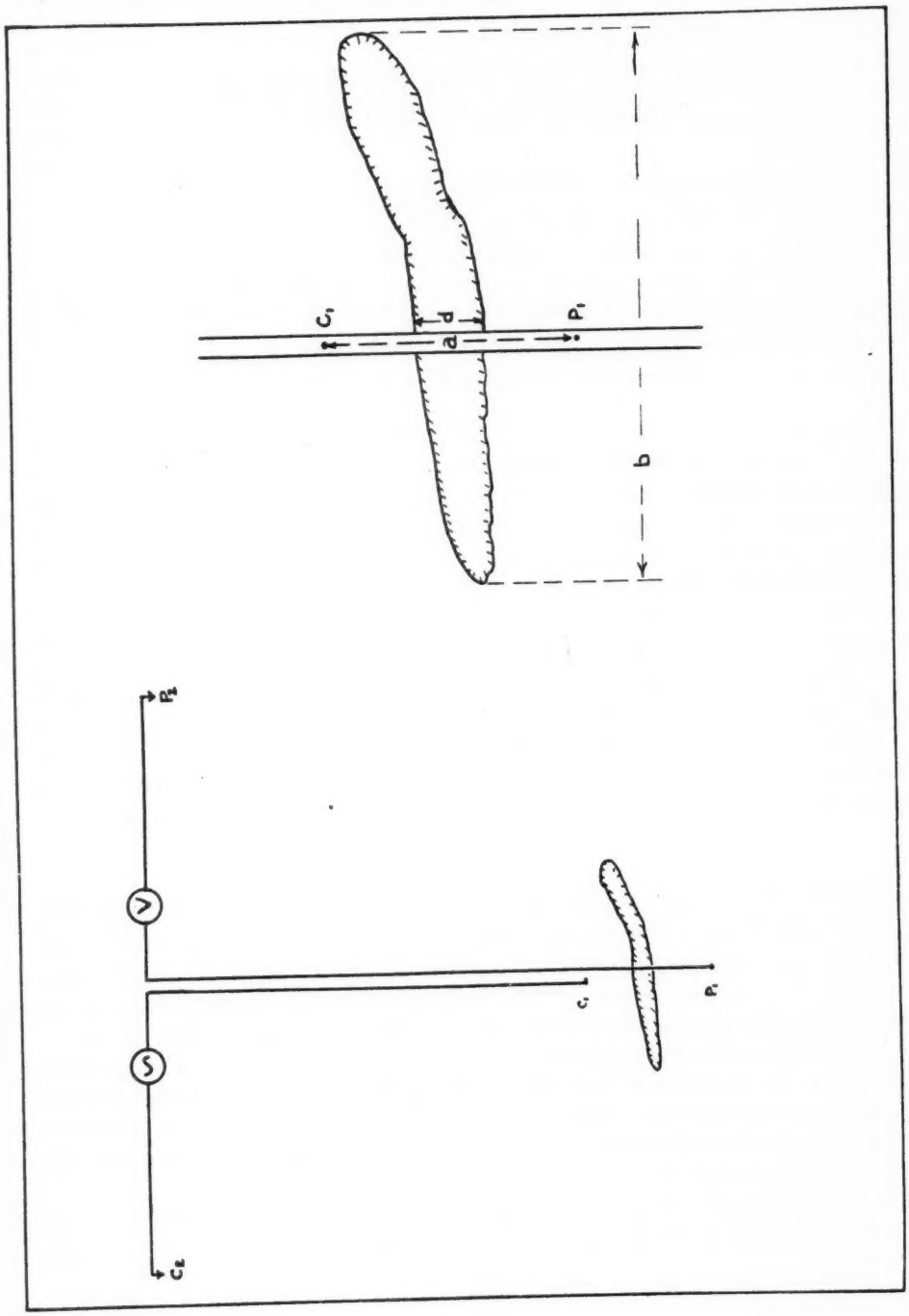

FIG. 1. Size determination configuration, normal array.

will tend to crowd into the good conducting material near C_1 and flow out the ends of the conductor remote from C_1. The net result is generally a robbing of current from the vicinity of P_1 and a lowering of the potential difference between P_1 and P_2. The magnitude of this effect depends on a number of things, including the ratio of conductivities, shape, and inclination of the body, and ratio of electrode spacing to length and thickness of the body. When there is a high conductivity contrast the ratio of electrode spacing to the length of the conductor is most important.

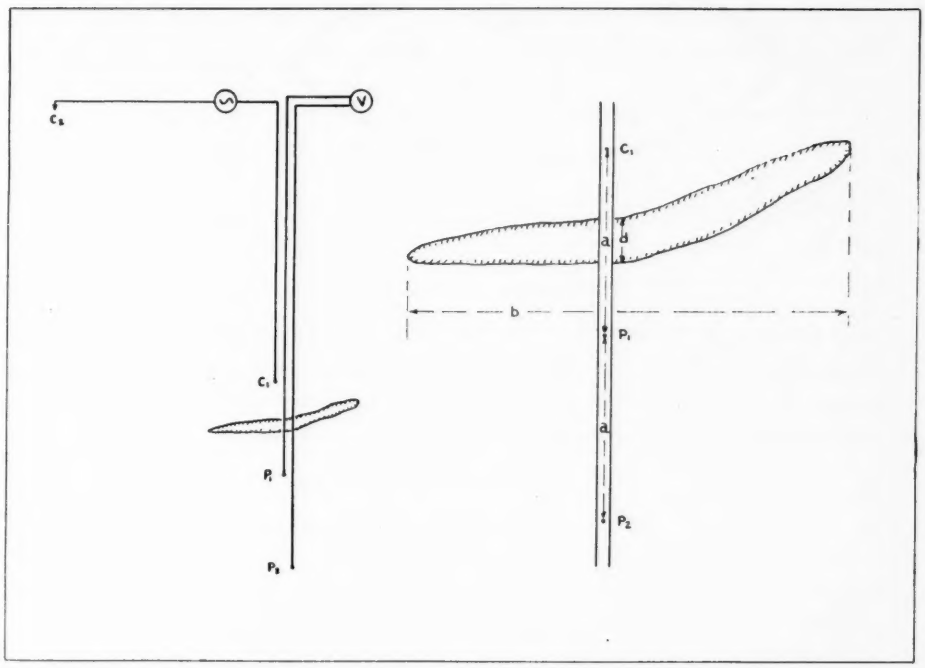

FIG. 2. Size determination configuration, equispaced three electrode array.

By varying the electrode spacing, i.e., by expanding about the intersection as center of C_1 P_1, we can vary the length of the conductor which is affecting our readings. The rate at which the observed voltages, or apparent resistivities calculated therefrom, return with increase of spacing to what may be considered characteristic of normal rock materials will be diagnostic as to the actual extension of the mineralization away from the intersection.

For quantitative interpretation a basis of comparison is required. Model experimental or theoretical curves drawn up for simple conventionalized bodies will serve the purpose. As an example of a body of reasonably adaptable shape which is amenable to theoretical treatment we may consider the oblate spheroid. The mathematical solution proceeds as follows:

POINT SOURCE ON AXIS OF OBLATE SPHEROID

Refer to figure 3 for the geometric configuration and coordinate system. The origin of a cartesian coordinate system is established at the center of the oblate spheroid. The z axis is taken along the axis of rotation of the spheroid and the

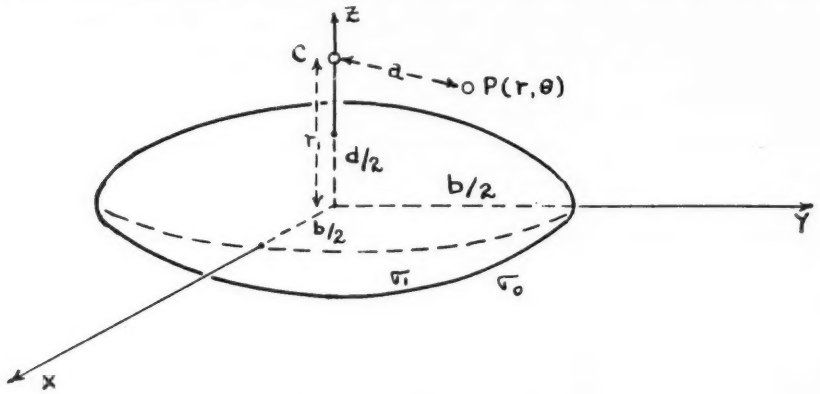

FIG. 3. Oblate spheroid problem, coordinate system.

x and y axes perpendicular to it. The length of the major axis of the spheroid is taken as b and of the minor axis as d. The conductivity of the ellipsoid is taken as σ_1, and that of the surrounding medium as σ_0. The transformation from cartesian to oblate spheroidal coordinates (r, θ, ϕ) is given by

$$\begin{aligned} x &= [r^2 + c^2]^{1/2} \sin\theta \cos\phi \\ y &= [r^2 + c^2]^{1/2} \sin\theta \sin\phi \\ z &= r\cos\theta \end{aligned} \tag{1}$$

for

$$\begin{aligned} 0 &\leqq \phi \leqq 2\pi \\ 0 &\leqq \theta \leqq \pi \end{aligned}$$

where

$$c = \tfrac{1}{2}[b^2 - d^2]^{1/2}.$$

Laplace's equation in the oblate coordinate system is given by

$$\frac{\partial}{\partial r}\left[(r^2 + c^2)\frac{\partial V}{\partial r}\right] + \frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left[\sin\theta\,\frac{\partial V}{\partial\theta}\right] + \left[\frac{1}{\sin^2\theta} - \frac{c^2}{r^2 + c^2}\right]\frac{\partial^2 V}{\partial\phi^2} = 0. \tag{2}$$

Since our configuration is axially symmetric the dependence on ϕ vanishes. The well behaved axially symmetric solutions obtained by separation of variables are given by

$$V_0 = \sum_{n=0}^{\infty} A_n Q_n\left(\frac{ir}{c}\right) P_n(\cos\theta) \quad \text{(exterior region)}, \tag{3}$$

$$V_1 = \sum_{n=0}^{\infty} A_n P_n\left(\frac{ir}{c}\right) P_n(\cos\theta) \quad \text{(interior region)}. \tag{4}$$

The reciprocal distance between two points (r, θ) and $r_1, \theta_1)$, one or both on the axis of rotation is given by[1]

$$\frac{1}{R} = \frac{i}{c} \sum_{n=0}^{\infty} (2n+1)\left[Q_n\left(\frac{ir}{c}\right) P_n\left(\frac{ir_1}{c}\right) P_n(\cos\theta) P_n(\cos\theta_1)\right] \text{ for } r > r_1. \tag{5}$$

$Pn\ (x)$ and $Qn\ (x)$ are the Legendre functions of the first and second kinds.

Consider the current source C at a distance r_1 from the center of the spheroid on the axis of rotation. The coordinates of the potential measuring point P are (r, θ), where r_1 is greater than r.

Ignoring a factor of $I/4\pi\sigma_0$ throughout, we set as our potential functions, interior and exterior to the spheroid,

$$V_0 = \frac{i}{c} \sum_{n=0}^{\infty} (2n+1)\left[Q_n\left(\frac{ir_1}{c}\right) P_n\left(\frac{ir}{c}\right) P_n(\cos\theta)\right] + \sum_{n=0}^{\infty} B_n Q_n\left(\frac{ir}{c}\right) P_n(\cos\theta) \tag{6}$$

—exterior solution, $r_1 > r$, and

$$V_1 = \sum_{n=0}^{\infty} A_n P_n\left(\frac{ir}{c}\right) P_n(\cos\theta) \tag{7}$$

as interior solution.

The boundary conditions that have to be satisfied at $r = d/2$ are

$$V_0 = V_1 \quad \text{and} \quad \sigma_0 \frac{\partial V_0}{\partial r} = \sigma_1 \frac{\partial V_1}{\partial r}. \tag{8}$$

Applying these we may obtain our coefficients An and Bn by equating coefficients of $Pn(\cos\theta)$.

Writing $\delta = \sigma_0/\sigma_1$, and expressing all distances in units of $d/2$ we find, as ratios of apparent to exterior resistivities.

$$\rho_a/\rho_0 = 1 + \frac{\alpha}{\epsilon} i(1-\delta) \sum_{n=0}^{\infty} \overline{B}_n Q_n\left(\frac{ir}{\epsilon}\right) P_n(\cos\theta) \tag{9}$$

in the exterior region, and

$$\rho_a/\rho_0 = \frac{\alpha}{\epsilon} i\delta \sum_{n=0}^{\infty} \overline{A}_n P_n\left(\frac{ir}{\epsilon}\right) P_n(\cos\theta) \tag{10}$$

in the interior region.

$$A_n = (2n+1)Q_n\left(\frac{ir_1}{\epsilon}\right)\left[\frac{Q_n'(i/\epsilon)}{P_n'(i/\epsilon)} - \frac{Q_n'(i/\epsilon)}{P_n(i/\epsilon)}\right] \Big/ \left[\delta\,\frac{Q_n'(i/\epsilon)}{P_n'(i/\epsilon)} - \frac{Q_n(i/\epsilon)}{P_n(i/\epsilon)}\right], \tag{11}$$

and

$$\overline{B}_n = (2n+1)Q_n\left(\frac{ir_1}{\epsilon}\right) \Big/ \left[\delta\,\frac{Q_n'(i/\epsilon)}{P_n'(i/\epsilon)} - \frac{Q_n(i/\epsilon)}{P_n(i/\epsilon)}\right] \tag{12}$$

where

$\alpha = a/d$ where a is the separation of the C and P.

$\epsilon = (b^2-d^2)^{1/2}/d$ is a measure of the eccentricity of the spheroid. For large ratios of b/d, ϵ is very nearly equal to b/d.

Tables of all the functions above are available (2) and formulae (9) and (10) may be readily evaluated numerically for any specific example.

When the potential measuring point is also on the axis of rotation of the spheroid and below the spheroid the equation (9) is further simplified.

Then

$$\theta = \pi \quad \text{and} \quad P_n(\cos\theta) = (-1)^n.$$

BASIS OF INTERPRETATION

So called "resistivity departure curves" have been prepared on the basis of equation (9) for the configurations of figures 1 and 2, for various values of ϵ, δ being taken as 1/200. These curves are presented in Figures 4 and 5 on a log-log basis. Points of interest are as follows:

(1) The curves for the equispaced three electrode array give more marked departures for the same disturbing body than the normal array.

(2) All curves return to "normalcy," i.e., ρ_a approximately equal to ρ_0, for the spacing slightly larger than the total lateral extent of the body. This qualitative rule will establish an upper limit to the average extent of the body from the hole.

(3) Curves for bodies of very limited lateral extent show a rapid return to normalcy with increased electrode spacing, and then an apparent increase in resistivity over ρ_0, falling asymptotically to an undisturbed condition with increasing spacing.

(4) Curves for bodies of more generous lateral extent show a slow rise and return to normalcy, with no marked excess over ρ_0.

(5) On the basis of these theoretical curves it appears possible to determine the proper value of ϵ within a factor of 2 without any difficulty. This value of ϵ

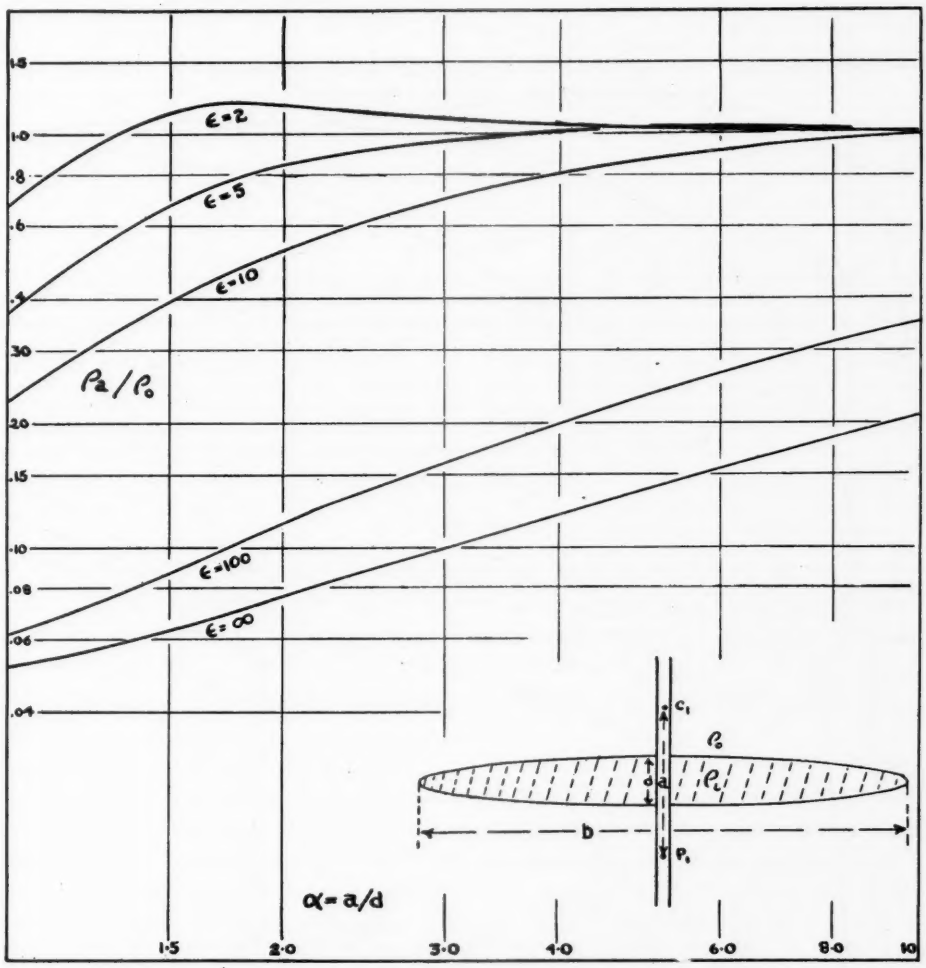

FIG. 4. Oblate spheroid resistivity departure curves, normal array.

will correspond to the oblate spheroid giving the same average potential disturbance as the actual ore body and will provide a reasonable estimate of the size of the body.

The special usefulness of the log-log plots of Figures 4 and 5 lies in that they permit one to match curve forms directly without entailing a knowledge of ρ_1 or even d.

Matching the form of the observed curve with a double family of curves for various ϵ and δ values will permit adequate quantitative interpretation to be made. A rough estimate of extent may be made if desired from the value of spacing at which the values first return to normalcy. This entails a knowledge of the approximate value of ρ_0.

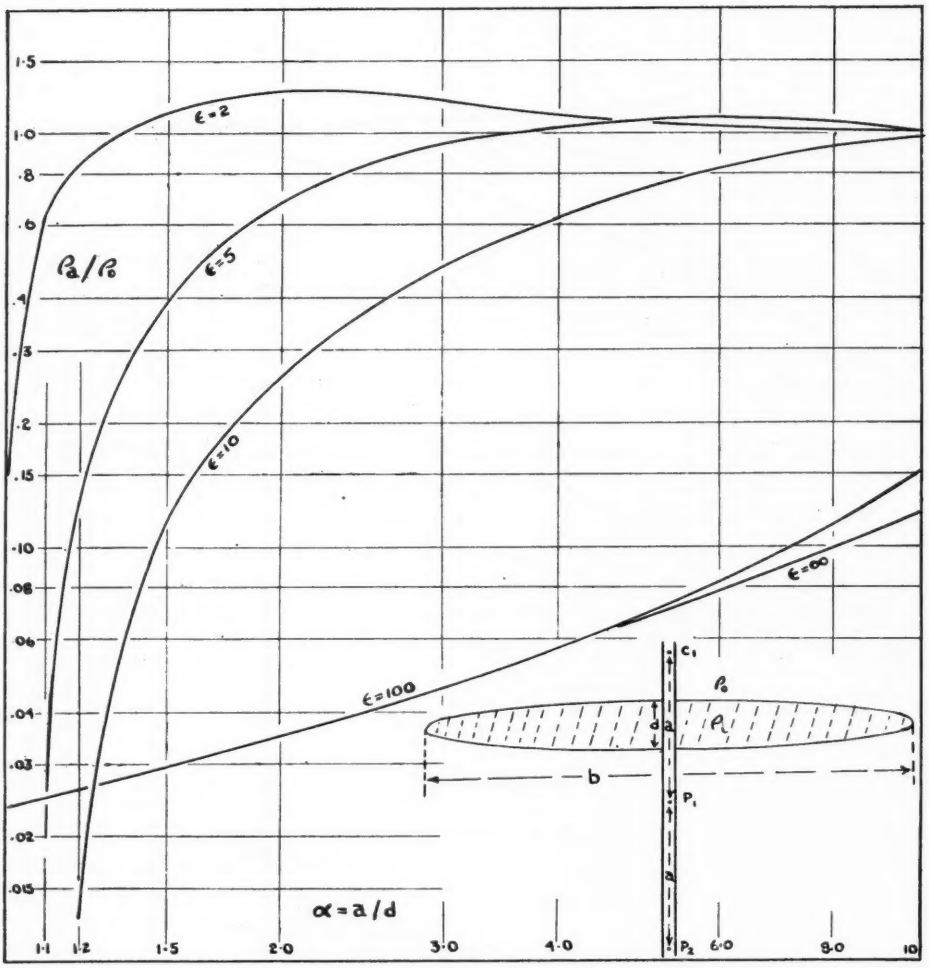

FIG. 5. Oblate spheroid resistivity departure curves, equispaced three electrode array, $\delta = 1/200$.

ACKNOWLEDGMENT

I wish to gratefully acknowledge the permission granted by Newmont Exploration Limited, of Jerome, Arizona, for permission to publish the material contained in this paper.

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SOUND RANGING IN A MEDIUM HAVING AN UNKNOWN CONSTANT PHASE VELOCITY*

WILLIAM SCHRIEVER†

ABSTRACT

A method for the sound ranging of explosions is described, in which the direction-angle of the explosion is given in terms of the ratio of the differences in the arrival times at two pairs of microphones, geophones, or hydrophones. It is unnecessary to know either the phase-velocity in the intervening medium or the absolute values of the time differences. However, the paths and the phase-velocities must be such that the time differences are the same as they would be for a wave-front traveling from explosion to the microphones at some constant velocity. A rapid graphical method for determining the locatien of the explosion is described. The precision of the determinations is discussed. Applications of the method to the scoring of bomb hits on bombing practice areas are suggested. The effect of the motion of the medium is considered.

INTRODUCTION

The theory for the sound-ranging methods used by our armed forces in the last world war was developed with the aid of the approximation that the wave front from the explosion was plane at the microphone array. If the angle subtended by a microphone array is so small that the wave-front may be considered plane, then the precision of determining the direction toward the explosion may be relatively poor.

Sound ranging methods may be used to locate explosions, or other sounds which deliver sufficient power to actuate arrays of microphones through air, water, or earth. Since such methods are likely to be used for military purposes, the theory for any usable microphone array must lead to calculations that are simple and that can be carried out very quickly.

The simple square array shown in Figure 1 has this desirable characteristic and in addition makes possible the determination of the direction toward the explosion without requiring a knowledge of the magnitude of the phase-velocity in the medium through which the waves travel.

DETERMINATION OF AZIMUTH ANGLE

In Figure 1 is depicted an array of four microphones located at the corners of a square at points (1), (2), (3) and (4), the length of the diagonal of the square being $2S$. The source of the sound, marked "Explosion," is located at a distance R from the intersection of the diagonals of the square, the direction of R making an angle θ with the (1), (3) diagonal as indicated. The distances from the explosion to the four microphones are respectively R_1, R_2, R_3, and R_4.

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If the time at which the explosion occurs is $t=0$, if the phase-velocity with respect to the earth of the explosion wave in the intervening medium is V in all directions, and if the arrival times of a wave-front at the four microphones are respectively t_1, t_2, t_3, and t_4, then we may write:

$$R_1 = Vt_1 \tag{1}$$

$$R_2 = Vt_2 \tag{2}$$

$$R_3 = Vt_3 \tag{3}$$

$$R_4 = Vt_4 \tag{4}$$

$$R_1 = (R^2 + S^2 - 2RS\cos\theta)^{1/2} \tag{5}$$

$$R_2 = (R^2 + S^2 - 2RS\sin\theta)^{1/2} \tag{6}$$

$$R_3 = (R^2 + S^2 + 2RS\cos\theta)^{1/2} \tag{7}$$

$$R_4 = (R^2 + S^2 + 2RS\sin\theta)^{1/2}. \tag{8}$$

By use of these equations $\tan\theta$ may be expressed as a function of S, R, and

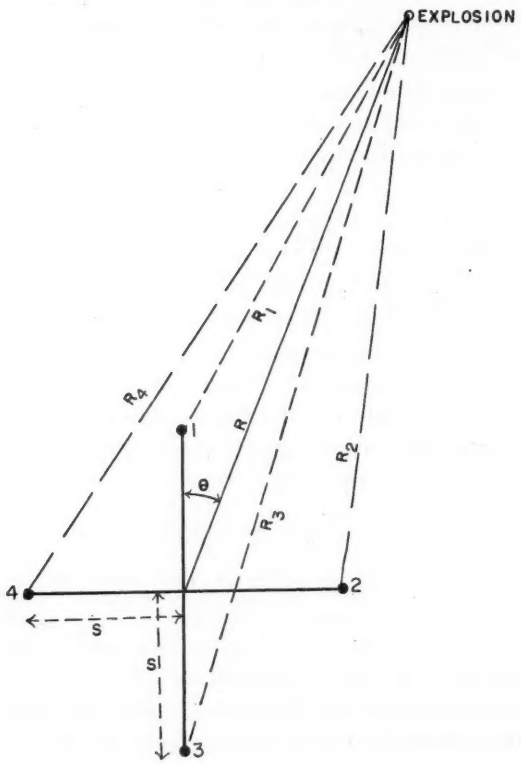

FIG. 1. A square array of four microphones makes possible the determination of the direction angle θ of the explosion in terms of the differences in arrival times of the wave-front at the four microphones.

the arrival-time differences at two pairs of microphones. Then by use of a justifiable approximation $\tan\theta$ may be expressed as just the ratio of two arrival-time differences. This solution will now be given.

From equations (5) and (7), and (6) and (8) we have:

$$R_3^2 - R_1^2 = 4RS\cos\theta \tag{9}$$

$$R_4^2 - R_2^2 = 4RS\sin\theta. \tag{10}$$

Dividing equation (10) by (9), we have:

$$\tan\theta = \frac{R_4 - R_2}{R_3 - R_1}\cdot\frac{R_4 + R_2}{R_3 + R_1} \tag{11}$$

which, in view of equations (1) to (8) inclusive becomes:

$$\tan\theta = \frac{t_4 - t_2}{t_3 - t_1}\cdot\frac{(R^2 + S^2 + 2RS\sin\theta)^{1/2} + (R^2 + S^2 - 2RS\sin\theta)^{1/2}}{(R^2 + S^2 + 2RS\cos\theta)^{1/2} + (R^2 + S^2 - 2RS\cos\theta)^{1/2}}. \tag{12}$$

The second factor on the right hand side of equation (12) may be shown to be one plus a negligible factor. Let $2RS/(R^2+S^2) = 2/(R/S - S/R)^2 = B$. Then the second factor may be written:

$$\frac{R_4 + R_2}{R_3 + R_1} = \frac{(1 + B\sin\theta)^{1/2} + (1 - B\sin\theta)^{1/2}}{(1 + B\cos\theta)^{1/2} + (1 - B\cos\theta)^{1/2}}. \tag{13}$$

The expansion of the binomials to third power terms leads to:

$$\frac{R_4 + R_2}{R_3 + R_1} = \frac{1 - \sin^2\theta\cdot B^2/8}{1 - \cos^2\theta\cdot B^2/8}. \tag{14}$$

It is to be observed that the first and third correction terms in B and B^3, respectively, disappear. In fact all the terms in the expansion containing odd powers of B disappear, and only the even powered terms remain.

Since the B^2 terms in equation (14) are small we may write it, in view of the definition of B:

$$\frac{R_4 + R_2}{R_3 + R_1} = 1 + \frac{\cos^2\theta - \sin^2\theta}{2(R/S - S/R)^2}. \tag{15}$$

The size of the second term on the right of equation (15), namely the second order correction term, may be checked by making $R/S = 10$ (e.g., $R = 10{,}000$ ft and $S = 1{,}000$ ft). Calculations show that if this correction term is neglected for θ equal to 1, 3, 5, 15, 30, 45, and 60 degrees, the mistakes in θ will be respectively only 1, 1, 3, 4, 4, 0, and 4 minutes of arc. These certainly are negligible.

Thus we may write for equation (11) the very close approximation:

$$\tan\theta = (t_4 - t_2)/(t_3 - t_1) = \Delta_{42}/\Delta_{31} \tag{16}$$

where the Δ's represent the time differences.

LOCATION OF EXPLOSION BY TWO ARRAYS OF MICROPHONES

In order to locate the source of the explosion another direction φ must be determined with another array of microphones. A scheme for doing this is shown in Figure 2. For the 5, 6, 7, 8 array of microphones we have:

$$\tan \varphi = (t_8 - t_6)/(t_7 - t_5) = \Delta_{86}/\Delta_{75}. \tag{17}$$

For an explosion located anywhere (in the figure) above the 4, 2, 8, 6 line, Δ_{31} and Δ_{75} will be positive. Then if $t_4 > t_2$, Δ_{42} is positive and the angle θ is positive as shown. If $t_4 < t_2$, Δ_{42} is negative and the angle θ would be to the left of the 3, 1 line. Similar conditions obtain for the 5, 6, 7, 8 array.

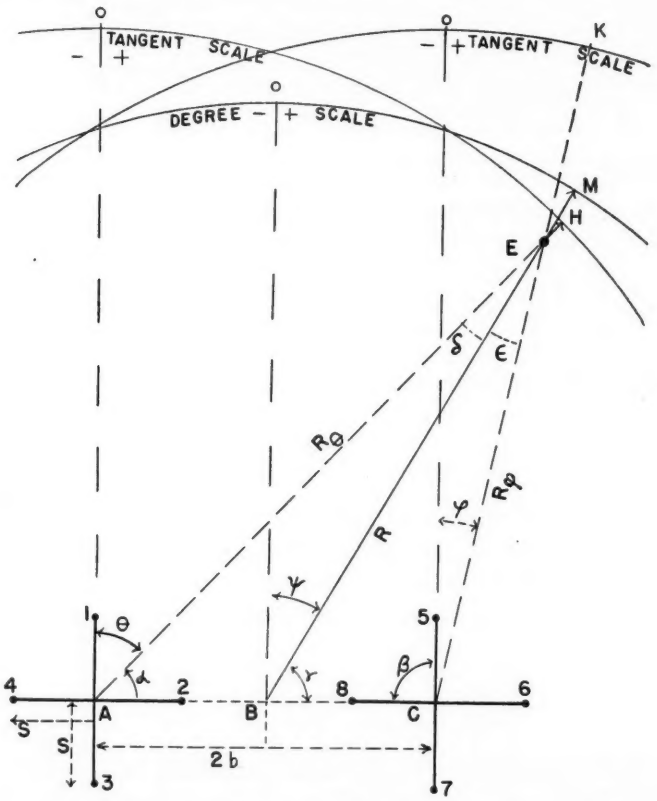

FIG. 2. Two square arrays of four microphones each make possible the rapid determination of the location of the explosion by employing a simple graphical method.

Absolute Values of Time-Differences Unnecessary

Since only the *ratios* of the time differences enter the equations for tan θ and tan ϕ, it is not necessary to know exactly at what rate the time-recording paper moves. It is only necessary to have the paper run at a constant rate for a few seconds while any one record is made. It is not necessary to have the same

rate for any other record. Thus it would not be necessary to have any exact timing device to control the speed of the paper, or to put time-lines on the paper. A transparent scale having lines spaced about 1/10 inch, and long enough to span the greatest time differences on the record, would serve very well to measure the time differences in arbitrary units.

Angles Independent of the Phase Velocity

Since equations (16) and (17) contain only time-differences the calculated magnitudes of the angles are independent of the phase velocity. In other words, any factor causing a change in the magnitude of the phase velocity will have no effect on the calculated values of the angles. There is this restriction: the phase velocity to each of the four microphones in one array must be changed by exactly the same amount.

GRAPHICAL LOCATION OF EXPLOSION

A graphical solution for the location of the explosion E (Figure 2) may be made rapidly with the aid of a properly constructed drawing board. On such a board the distance between the centers of the two microphone arrays is laid off to a suitable scale, as AC in Figure 2.

A radius arm pivoted at point A swings over the "Tangent Scale" on which point H lies, the zero of the scale being on the line through microphones 3 and 1. This radius arm swings through an angle θ such that the numerical value on the tangent scale at H is equal to the calculated value of Δ_{42}/Δ_{31}. A straight line along this arm will pass through A and the explosion point.

Another radius arm pivoted at C swings over the other "Tangent Scale" on which point K lies. If this arm is set so as to pass through the point K on this scale, whose numerical value is equal to Δ_{86}/Δ_{75}, then line CK also passes through the explosion point. The point of intersection of AH and CK, marked E, is the location of the explosion.

A third radius arm pivoted at B so as to swing over the "Degree Scale," (to M in Figure 2) and having distances in yards marked off to proper scale from point B along its length, may be used to determine the azimuth angle ψ and the distance R to the explosion at E.

PRECISION OF THE METHOD

In order to determine the precision with which the azimuth angle ψ and the radius vector R of the explosion point, can be found by the method described herein, it is convenient first to arrive at expressions for γ, R, R_θ, and R_φ of Figure 2.

It can be shown with the aid of Figure 2 that:

$$\cot \gamma = \tfrac{1}{2}(\cot \alpha - \cot \beta) = \tfrac{1}{2}(\tan \theta + \tan \phi) \tag{18}$$

which, in view of equations (16) and (17) may be written:

$$\cos \gamma = \tfrac{1}{2}(\Delta_{42}/\Delta_{31} + \Delta_{86}/\Delta_{75}). \tag{19}$$

From Figure 2 it may also be shown that:

$$R = b/(\sin \gamma \tan \theta - \cos \gamma) \tag{20}$$

which together with equation (18) make it possible to write:

$$R = b[4 + (\tan \theta + \tan \phi)^2]^{1/2}/(\tan \theta - \tan \phi). \tag{21}$$

Equations (16) and (17) make it possible to express R of (21) in terms of b and the ratios of the time differences Δ_{42}/Δ_{31} and Δ_{86}/Δ_{75}. Again from Figure 2 it may be shown that:

$$R_\theta = b/(\sin \theta - \cot \gamma \cos \theta). \tag{22}$$

By use of equations (16), (19) and (22), R_θ may be expressed in terms of b and the four time differences Δ_{31}, Δ_{42}, Δ_{75} and Δ_{86}.

Similar considerations yield a value for $R\varphi$. It may be expressed:

$$R\varphi = b/(\cos \phi \cot \gamma - \sin \phi). \tag{23}$$

Theory for Small Mistakes

If $y=f(x, u, v, \text{etc.})$ where x, u, v, etc., are each measured independently, and if dx, du, dv, etc., are small mistakes in x, u, v, etc., respectively, then the resulting maximum mistake in y is given by:

$$|dy| = |dx\partial y/\partial x| + |du\partial y/\partial u| + |dv\partial y/\partial v| + \text{etc.} \tag{24}$$

The absolute values are chosen since the unknown small mistakes in the independent variables may be either plus or minus, thus making it possible for all terms in equation (24) to have the same sign.

In calculating the maximum mistakes in the following paragraphs it will be assumed that the phase velocity in the medium is 1,000 ft/sec, that R or R_θ is 10,000 ft (Figure 2), that S is 1,000 ft, that b is 2,000 ft, and that the time differences, the four Δ's, are determined to ± 0.002 sec.

Maximum Mistakes in θ and ϕ

Applying equation (24) to equation (16) we have:

$$|d\theta| = |\cos^2 \theta/\Delta_{31}| \, (|d\Delta_{42}| + |d\Delta_{31}(\Delta_{42}/\Delta_{31})|). \tag{25}$$

The conditions specified in the preceding paragraph make, $\Delta_{31} \simeq 2$ sec, and $\Delta_{42} \simeq 0$ when $\theta \simeq 0$. Thus equation (25) yields $|d\theta| = 0.001$ radian or 3.4 minutes of arc.

For $\theta \simeq 30$ degrees, $\Delta_{31} \simeq 1.73$ sec and $\Delta_{42} \simeq 1$ sec, and equation (25) yields $|d\theta| = 0.00136$ radian or 4.5 minutes of arc.

For $\theta \simeq 45$ degrees, $|d\theta| = 0.0014$ radian or 4.7 minutes of arc.

Since ϕ is determined in exactly the same way as θ, the maximum values of the mistakes $|d\phi|$ will be the same as those for θ.

Maximum Mistake in γ

The application of equation (24) to equation (18) yields:

$$|\,d\gamma\,| = \tfrac{1}{2}\sin^2\gamma(\,|\sec^2\theta d\theta\,| + |\sec^2\phi d\phi\,|\,). \tag{26}$$

With the aid of a scale-drawing and graphical calculations, values were computed by use of equation (26) for the maximum mistake in γ, namely $|d\gamma|$, for explosion positions such that θ had the values 0, 30 and 45 degrees. The results are shown in Table I.

TABLE I

$\theta°$	$\phi°$	$\gamma°$	$\lvert d\theta\rvert$ rad.	$\lvert d_\varphi\rvert$ rad.	$\lvert d\gamma\rvert$ rad
0	−22	101.6	0.001	0.0013	0.00120
30	+ 8	70.5	.00136	.001	.00114
45	+26.3	53.5	.0014	.0013	.00142

Thus the maximum mistake in the azimuth angle ψ, which is the complement of γ, is not greater than 0.00142 radians Ω 4.9 minutes of arc.

Maximum Mistake in R

The application of equation (24) to equation (21) yields:

$$|\,dR\,| = \left|\frac{b\sec^2\theta}{m}\left(\frac{n}{(4+n^2)^{1/2}} - \frac{(4+n^2)^{1/2}}{m}\right)d\theta\right| + \left|\frac{b\sec^2\phi}{m}\left(\frac{n}{(4+n^2)^{1/2}} + \frac{(4+n^2)^{1/2}}{m}\right)d\phi\right| \tag{27}$$

where $m \equiv \tan\theta - \tan\phi$ and $n \equiv \tan\theta + \phi$.

With the aid of graphical calculations and the data in Table I, equation (27) yields for $\theta = 0°$, 30° and 45° respectively, the values of $|dR|$, 23 ft, 62 ft and 84 ft.

It is clear that if the lengths in Figure 2, S, b and R, were multiplied by the same factor k, the angles would remain the same size and the precision of determining R would remain ± 23, 62 and 84 ft ($d\theta$ and $d\phi$ would be multiplied by a factor $1/k$ but b would be multiplied by k thus keeping $|dR|$ the same.)

It is also clear that in "ranging" an explosion at a given place greater precision may be achieved by increasing S and b and also by measuring the time differences with greater precision.

EFFECT OF THE MOTION OF THE MEDIUM

For the foregoing developments the assumption was made that the microphones and the intervening medium were at rest with respect to the earth. If all the medium between the explosion and the two arrays of microphones has a velocity V_{me} with respect to the earth, and if the velocity of the phase is V_{sm}

with respect to the medium, then the phase velocity with respect to the earth, V_{se}, is given by the vector sum:

$$\vec{V}_{se} = \vec{V}_{sm} + \vec{V}_{me}.$$

Since the various wave-front velocities with respect to earth are along the lines, explosion point to microphone; since these lines make different angles with respect to V_{me}, which in the simplest case is constant in magnitude and direction; and since V_{sm} is constant in magnitude; V_{se} has a different magnitude in each microphone direction.

A rather lengthy investigation revealed that in the determination of θ by the equation $\tan\theta = \Delta_{42}/\Delta_{31}$ if either the 3, 1 or the 4, 2 pair of microphones subtends an angle at the explosion of only 7.8 degrees, a cross-wise motion of the medium (Figure 2) of only one mile per hour would cause as much mistake in the location of the explosion as would a mistake of 0.002 sec in the time differences. ($S = 1{,}000$ ft, $V = 1{,}000$ ft/sec, $b = 2{,}000$ ft). A motion of the medium from top toward bottom of Figure 2 of 7.2 mi/hr would cause a mistake of the same size as that caused by the one mi/hr cross-wise motion of the medium.

Thus the relatively simple foregoing developments for the azimuth angle ψ and the radius R do not lead to correct results when the velocity of the medium relative to the earth is appreciable in comparison to the velocity of the wave-front relative to the medium.

However it is interesting to note that the square microphone array, which was chosen for the foregoing developments, does automatically make effective compensation for the motion of the medium. The approximations which have been made lead to the same result as would the assumption of a plane wave front over one square array. This is true because the first order correction terms dropped out for this particular pattern of detectors. If it is assumed that the explosion is so distant that the wave front is very nearly plane over one array, then the change in V_{se} produced by the velocity of the medium will be the same for all four paths to the detectors. Thus the phase velocity with respect to the earth will be constant and therefore the equation $\tan\theta = \Delta_{42}/\Delta_{31}$ will give the correct direction angle θ. The velocity V_{se}, for the other square array, in general will be different but it will be constant for the four paths to that array of detectors, and therefore the equation $\tan\phi = \Delta_{86}/\Delta_{75}$ will also give the correct direction angle ϕ. Therefore the scheme proposed in this paper does yield correct results when the medium is in motion if the wave front over one square array of detectors is essentially plane.

POSSIBLE APPLICATIONS

It appears that a promising application of this proposed method of sound-ranging may be made to the scoring of bomb-hits on bombing practice areas. If each bomb contains a small amount of explosive which will be detonated at impact, then refracted seismic waves will travel to the eight geophones in the

two rectangular arrays illustrated in Figure 2. Since the geophones can be planted at such depths that the travel times of the refracted wave up from the nearly horizontal refracting interface at the various geophones are the same, the differences in the total travel times will be caused by different path-lengths in the highest velocity medium. Thus these time differences meet the conditions required for calculating θ and ϕ by equations (16) and (17), and the rapid graphical method for locating the explosion can be used. In the matter of a minute or so the bomber-trainee can then be informed by radio exactly where his bomb has struck with respect to the target. For this application the distance could be measured from the bombing target and the azimuth angle could be measured from the geographic or the magnetic north.

It appears also that the method can be applied to bombing-practice over water. In this case the sound of the exploding bomb will travel through the water and the geophones will be replaced by hydrophones.

Off-shore explosions may also be located by suitable arrays of hydrophones. It is possible to have several extra hydrophones located far out ahead of the two square arrays, which, when actuated by an incoming signal, will start the recording paper in time to record the arrivals of that signal at the hydrophones of the two arrays.

USE OF THE WAVE HEIGHT OPERATIONAL INDEX IN PLANNING OFFSHORE GRAVITY METER SURVEYS*

A. H. GLENN† AND R. W. JAMES†

ABSTRACT

Efficiency of offshore gravity meter exploration (stations occupied daily) is analyzed statistically as a function of wave height. For the surveys investigated, the number of stations occupied daily can best be represented by the line of regression, $Yc=49.85-8.75X$, where X equals wave height (as defined herein), and Yc equals number of stations. Cost of offshore gravity meter surveys is shown to vary as much as 50 percent depending on planning involving sea conditions. Application of forecasts of sea and weather conditions is discussed and savings achieved through their use are demonstrated.

INTRODUCTION

Based on experience gained in furnishing weather and sea forecasts to offshore exploration parties during the 1948–1949 period, Glenn and Bates (1, 2) proposed the following indices of the efficiency of offshore gravity meter exploration with respect to sea conditions.

Maximum Wave Height	*Operational Performance*
0 to 4 feet	Safe, Efficient
4 to 6 feet	Marginal
Over 6 feet	Dangerous and/or Inefficient

With the acquisition of additional operational data, it has been possible to study these criteria in detail, and to present a more refined index than that above, which was based largely on a poll of subjective opinions of offshore exploration parties. It is interesting to note wherein the indices based on subjective opinion agree with objective objective analysis and where disagreement exists.

DESCRIPTION OF DATA

It is evident that the speed with which stations can be occupied for gravity measurement depends on a number of factors such as:

1. The station spacing (i.e., in a regional survey running time between stations is greater than in a detail survey).
2. Type of gravity meter used (i.e., time on station depending on efficiency of leveling, natural period of meter in relation to prevailing microseisms, etc.).
3. Distance of survey from port.
4. Type of vessels, holding tackle, etc., employed.
5. Method of horizontal control employed.

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6. Proximity of survey to shipping lanes.
7. Bottom conditions.
8. Occurrence of fog.
9. Sea conditions.

Factors 1 through 6 are relatively fixed once the survey commences. Thus the principal variables thereafter affecting efficiency are factors 7, 8, and 9.

During the past year operational records of some of the regional gravity meter surveys employing shoran horizontal control were obtained. These surveys were made off the Texas and Louisiana coasts on grids extending seaward 20 to 30 miles. The spacing of stations was approximately 1 to 2 miles. The records applied to operation of the larger boats used in this work, principally war surplus craft, ranging in length from 85 to 110 feet and having drafts of 5 to 7 feet. Although there are substantial differences in operational performance of boats depending on their size, the data presented herein indicated that the response of the smaller boats to wave action was not markedly different from that of the larger boats in *these length ranges*.

Inspection of the operational records turned up a total of 187 days' data which were believed free of major influences on operations other than sea conditions, and for which simultaneous wave, wind, and weather observations were available.

There are several elements included under the term "sea conditions" which affect the gravity meter operation: wave height, wave period (whether short, choppy waves, or swell), direction of the wave trains, current velocity, and wind velocity. Of these elements, the most important in the Gulf of Mexico proves to be the wave height. The other elements sometimes cause striking effects on efficiency, but as a reliable, measurable index of efficiency on a long term basis, wave height is most important.

The data used in this study were received in the form shown in Table 1:

TABLE 1

FORM OF OPERATIONAL DATA USED IN STATISTICAL ANALYSIS

Date	March 5	6	7	8	9	10
No. of obs. Boat "A"	29	28	16	6	0	0
No. of obs. Boat "B"	32	0	15	10	0	0
No. of obs. Boat "C"	26	20	10	4	0	0
Remarks on Weather and Operations	Fair Wea.	Fair Wea. Boat repairs on "B"	Strong SE wind	5′ swells	Days Off	Days Off

DEVELOPMENT OF WAVE HEIGHT OPERATIONAL INDEX

Data of the form indicated in Table 1, combined with extensive observational wave data now available for the northwestern Gulf coast provide an opportunity for application of statistical methods. Figure 1 is a scatter diagram of the num-

ber of gravity observations made daily *vs* the wave height for the particular day. The wave height compared with each day's operational data is the average of the maximum wave reported in the operating area at 6 AM and 6 PM of the day in question. The wave observations (to the nearest $\frac{1}{2}$ foot) were made both on the boats and at certain offshore drilling and production platforms, and are in agreement with wind conditions existing over the Gulf at the time.

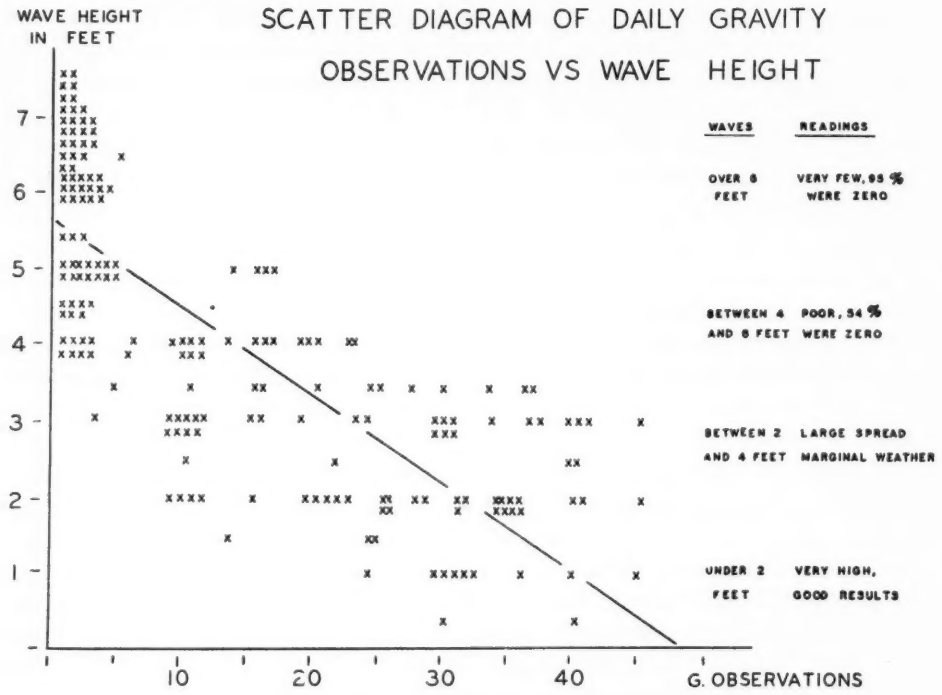

FIG. 1

It is evident from the scatter diagram that the following relations between efficiency and wave height applied in these surveys.

1. When wave height is less than 2 feet, a high number of gravity observations are made daily.
2. In the 2 to 3.5 foot wave range, a large scatter in the number of observations is shown. This would indicate that other factors, possibly wave period, or current conditions had a significant effect on efficiency in this range.
3. In the 4 to 5.5 foot maximum wave range, a relatively low number of observations were made (marginal operating conditions).
4. Above the 6 foot limit, efficiency was very low. Only a few readings were made daily.

Figure 2 shows the average number of gravity observations made daily

under various wave height conditions. The average range was from 31.6 observations daily with waves less than 2 feet to 0.3 observations daily when waves exceeded 6 feet.

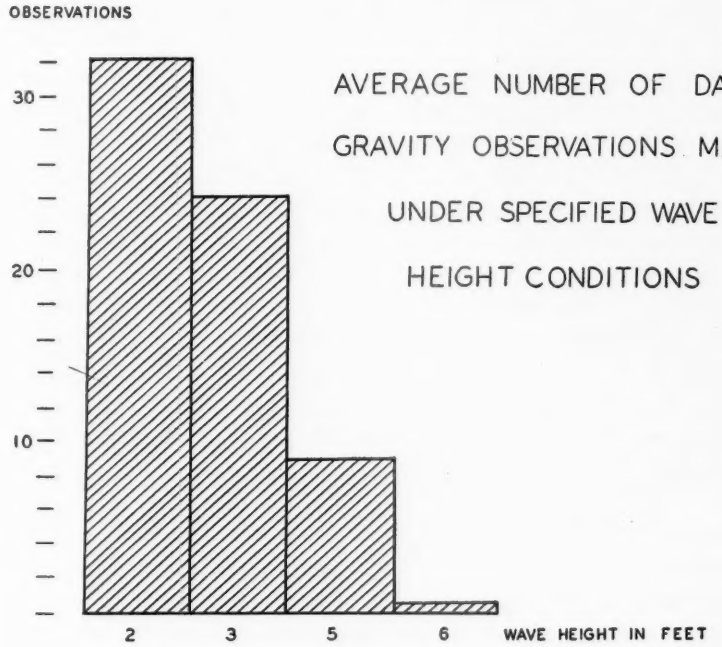

FIG. 2

Shown in Figure 3 is the correlation table classifying the data for several computations, as follows:

1. The correlation coefficient, $r=0.705$ indicates a high relationship between wave height and number of observations made.
2. The standard error of estimate shows 68 percent of the cases to fall within 8.2 observations of the line of regression; 50 percent of the cases within 5.5 observations; and 95 percent within 16.4 observations.
3. The line of regression is shown in Figure 4. Expressed algebraically $Y_c=49.85-8.75X$. Thus at a maximum wave height equal to 6 feet, Y_c, the number of observations expected is nearly zero, and when waves fall to 1 foot, approximately 40 gravity observations can be expected daily.

These relationships, included under the term, WAVE HEIGHT OPERATIONAL INDEX, are of significant economic importance through their use in planning offshore gravity meter work, both on the advanced and field planning levels. The remainder of the paper is devoted to development of these applications.

CORRELATION TABLE

Y \ X	0.00 1.99	2.00 3.99	4.00 5.99	6.00 7.99	8.00 9.99	F_y	D_y	$F_y D_y$	$F_y D_y^2$	$F_y D_x D_y$
0-5		$_{0}4^{0}$	$_{2}32^{64}$	$_{4}28^{116}$	$_{8}15^{90}$	80	2	160	320	270
6-10		$_{0}15^{0}$	$_{1}11^{11}$	$_{2}1^{2}$		27	1	27	27	11
11-15	$_{0}1^{0}$	$_{0}4^{0}$	$_{0}4^{0}$			9	0	0	0	0
16-20		$_{0}8^{0}$	$_{-1}5^{5}$			13	-1	-13	13	-5
21-25	$_{2}2^{4}$	$_{0}7^{0}$	$_{-2}2^{4}$			11	-2	-22	44	0
26-30	$_{3}2^{6}$	$_{0}15^{0}$				17	-3	-51	153	6
31-35	$_{4}5^{20}$	$_{0}11^{0}$				16	-4	-64	256	20
36-40	$_{5}2^{10}$	$_{0}9^{0}$				11	-5	-55	275	10
41-45	$_{6}1^{6}$	$_{0}1^{0}$				2	-6	-12	72	6
46-50	$_{7}1^{7}$					1	-7	-7	49	7
F_x	14	74	54	30	15					
$F_x D_x$	-14	0	54	60	45					
$F_x D_x^2$	14	0	54	120	135					

X=WAVE HEIGHT IN FEET Y=GRAVITY OBSERVATIONS

FIG. 3

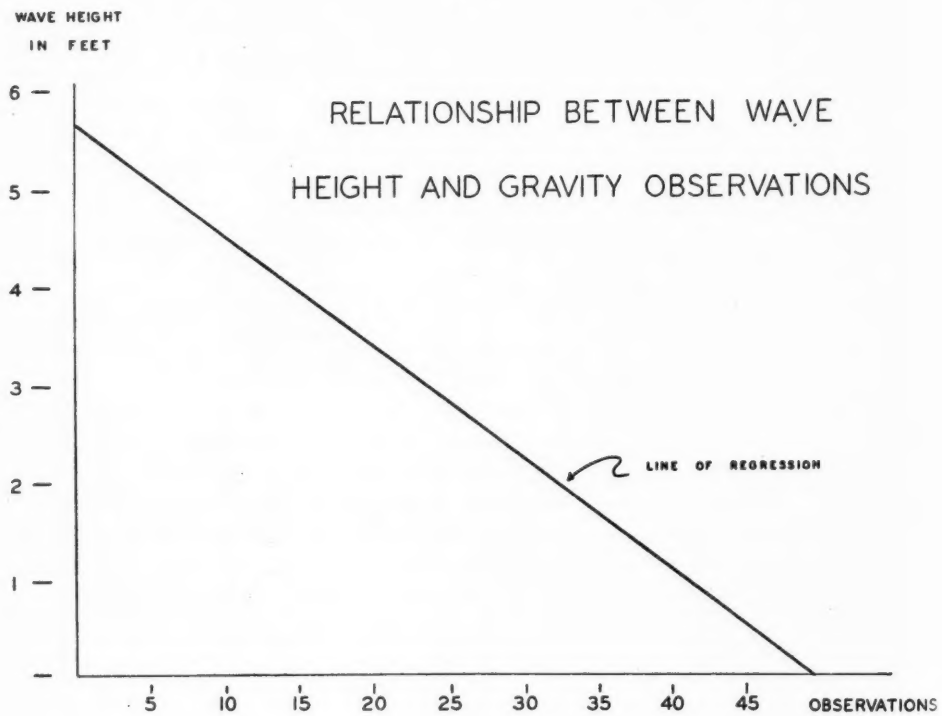

FIG. 4

USE OF THE WAVE HEIGHT OPERATIONAL INDEX IN ADVANCED PLANNING

With the INDEX known, it is evident that an accurate forecast of wave height is equivalent to a forecast of operational efficiency. In the advanced planning of a survey there are several ways to estimate the wave conditions that can be anticipated. In order of preference these are:

1. Through climatological analysis of wave observations made in the area: (for example, A. H. Glenn and Associates' files of wave data for the Texas and Louisiana coasts now comprises approximately 20,000 individual observations taken at six hourly intervals each day during the period from April 1948 to the present. Supplemented by the file of approximately 100,000 generalized wave observations made in the Gulf of Mexico by ships, it is possible to furnish accurate estimates of the mean and extreme wave conditions in these areas. Similar shipboard data are available for such areas as Lake Maracaibo, the Persian Gulf, Gulf of Venezuela, Indonesia, West Indies, etc.).
2. Through correlation of generalized wave observations and wind records: (Bates' method (3) of deriving refined breakdowns of wave height ranges in feet using summaries of ship sea observations and wind data is the principle technique employed here.)
3. Development of data through wave calculations made from past weather maps: (This method employs the "hindcast" of wave conditions which occurred in the past, then a climatological summary of these "hindcasted" wave conditions. The method provides acceptable results only in the hands of a meteorologist experienced in wave forecasting in the area. It is not generally employed since a meteorologist so qualified has studied enough wave data to obviate the need for the technique. This method of developing wave data is excessively laborious and consequently expensive and its use in the Gulf area appears unjustified in view of the superiority of methods listed under 1 and 2. This opinion is corroborated by Pierson's work (4) on the Atlantic coast).

Figure 5 shows a summary of maximum wave heights at two locations approximately 35 miles apart in the Northwestern Gulf area. The zones around these two locations have been extensively surveyed, and ordinarily are worked from different ports. In A. H. Glenn and Associates' files 2,189 wave observations were available for Zone B. A longer record was available for Zone A but for purposes of direct comparison the same period of record (February 1949 to January 1951) was summarized for which 2,575 observations were available.

By use of the line of regression, Figure 4, and Figures 2 and 5 the wave data can be interpreted in terms of the number of gravity observations that can be made in these zones each month. In this example, Figure 6, a month of 30 working days, and a detailed survey (station spacing of 1 mile) was assumed.

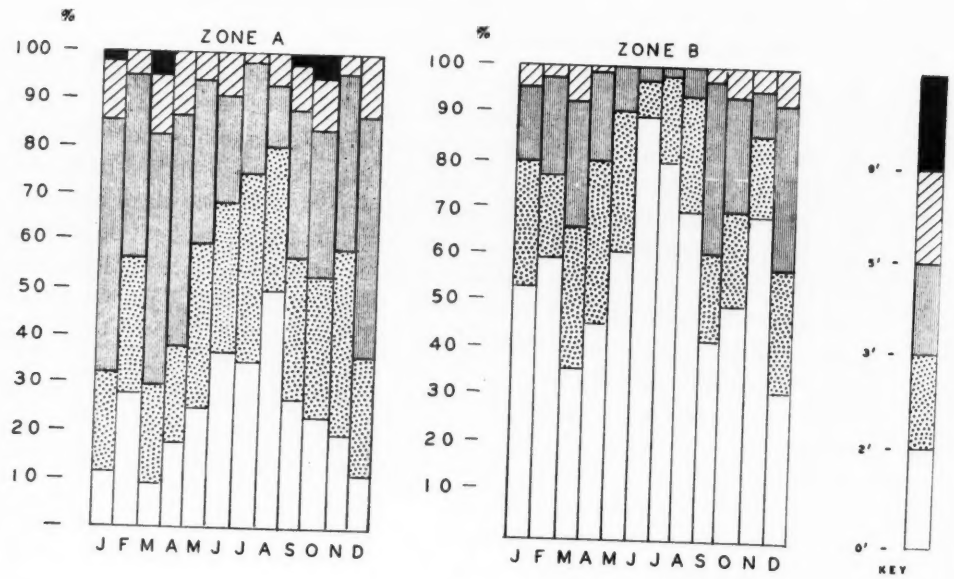
AVERAGE DISTRIBUTION
OF WAVE HEIGHTS
%
ZONE A
100
90
80
70
60
50
40
30
20
10
J F M A M J J A S O N D
%
ZONE B
100
90
80
70
60
50
40
30
20
10
J F M A M J J A S O N D
9'
5'
3'
2'
0'
KEY

FIG. 5

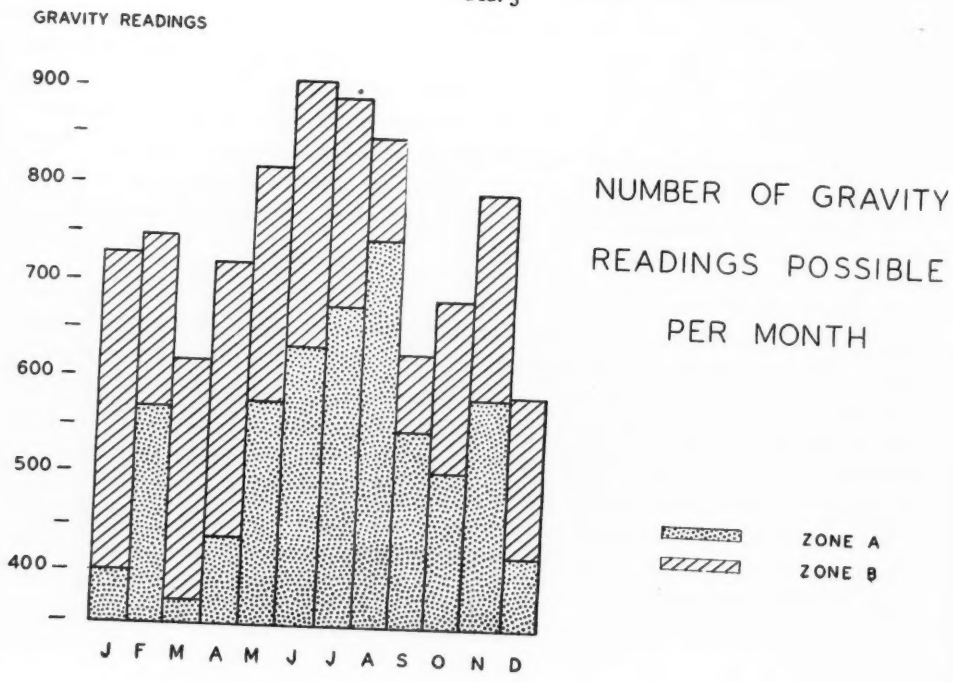
GRAVITY READINGS
900
800
700
600
500
400
J F M A M J J A S O N D
NUMBER OF GRAVITY
READINGS POSSIBLE
PER MONTH
ZONE A
ZONE B

FIG. 6

It is evident that marked seasonal and regional differences between those two nearby zones exist. Consider some of the conclusions which can be made subject to the limitations of the standard error of estimate, and climatological probability (a point discussed later).

1. A 2,000 station survey is to be made in zone A, with 2 gravity meter boats (at an assumed $500 per day) and 2 shoran boats (at an assumed $200 per day). If the survey starts March 1 it can be completed May 10, but if it starts July 1 it can terminate August 13. The difference is approximately 27 crews days or about $43,000. This does not take into consideration associated costs of the shore personnel whose efficiency depends on rate of receiving data.
2. A survey of 2,000 stations is to be made in zone A and another 2,000 station survey in zone B (with the same party). If the survey starts in zone B on June 1 it can be completed August 16 in zone A (76 crew days). If it starts in zone B on January 1 it can be completed in zone A on April 18 (108 crew days), a difference of $48,000.
3. A 2,000 station survey in both zone A and zone B is to be commenced on March 1. If zone A is worked first, the survey will terminate in zone B on June 15. If zone B is worked first, the survey will terminate in zone A on June 10, a difference of $7,500.

In considering these examples, it should be remembered that they are adjacent operating areas. If operations over an entire coast (from Galveston to Breton Sound, for example) are studied, one finds greater seasonal and regional differences in wave conditions which can either be used to advantage or ignored with possible loss of time.

Other possibilities in the use of the index are:

1. By knowing the duration of the periods of favorable and unfavorable wave conditions, it can be determined whether it is more economical to pay overtime and make full use of all good weather, or whether a definite schedule (say 10 days on and 4 days off) is more economical.
2. It can be ascertained if a persistent day-to-night variation in wave height occurs, and providing it does, if night operations are practical and economical.
3. Selection of vessels for efficient performance under expected wave action.

These latter examples require greater development than is possible in a paper of this scope.

The advanced planning can not, of course, eliminate weather difficulties entirely, but in the advanced planning, use is made of the known seasonal, regional, and daily variations in wave conditions, to achieve the most efficient scheduling. The question arises as to whether these seasonal, regional and daily characteristics can be relied upon in planning or whether "average" conditions are simply

an arithmetical mean with no physical significance when interpreted in terms of climatic conditions in a particular year. The reliability of climatic data for planning purposes must be evaluated for each individual case. In some instances climatic data only provide a gross index and in other cases a highly refined index. As a generalization, in the areas of current petroleum operations, the reliability of climatology is inversely proportional to latitude. In the latitude of the Gulf of Mexico use of climatological wave data developed under methods 1 or 2 above has proven successful. For example, the distribution of wave heights in zone A in Figure 5 has been found to represent actual conditions in any given year for any category of wave height within ± 5.5 days. This is the poorest approximation to actual conditions that occurred while the data were generally accurate within 2.5 days (approximately 10 percent). The data indicate that there is more variation in the year to year distribution of wave heights in winter than in summer but the overall accuracy is believed adequate for planning purposes.

USE OF THE INDEX IN FIELD PLANNING

In the maintenance of efficiency on a week-to-week basis after the survey commences, climatological interpretation of the index is limited by the fact that the particular days on which the various wave conditions will occur is not known and long range forecasting has not provided a significant improvement over climatological probabilities. Instead, 48 hour forecasts of wave heights which can be interpreted in terms of operational performance are in use by offshore exploration crews on the Gulf coast. As indicated by Graham and Geyer (5) and James (6), the accuracy of these forecasts is such that, as a long term average, 9 out of 10 24 hour forecasts are within 1.5 feet of observed conditions, and 8 out of 10 48 hour forecasts are within 1.5 feet of observed conditions.

In application, the use of the forecasts takes several forms and a complete discussion is beyond the scope of the paper. Considering an example, Figure 7 shows a 48 hour forecast prepared for an offshore gravity crew working along the northwestern Gulf coast.

An interpretation of these data in terms of operations would be along the following lines.

1. Shallow water stations can not be made efficiently late Tuesday due to excessive instrument noise caused by SE swell. If observations from such stations are desired on Tuesday, they should be made early. Between 6 and 8 AM, 6 observations per hour are possible, while by noon only 1 observation per hour will be possible.
2. Deep water observations should be scheduled for Tuesday afternoon. Efficiency in deep water will be falling off to approximately 1 station per hour by sun-down Tuesday; but shallow water work would be impractical late Tuesday.

A. H. GLENN & ASSOCIATES FORM 8

†METEOROLOGICAL-OCEANOGRAPHIC DATA ISSUED 6 AM CST DECEMBER 10, 19 –

FOR A B C COMPANY LOCATIONS IN "X" AREA

THE GENERAL WEATHER SITUATION AT 6 AM CST DECEMBER 10 19 –

HIGH PRESSURE AREA CENTERED NE OF GULF WILL MAINTAIN INC. SE WIND AND SWELL IN "X" AREA TODAY AND EARLY WED. STRONG NORTHER NOW MOVING SE PAST DALLAS AND MEMPHIS EXPECTED TO PASS "X" AREA LATE WED. MORN., CAUSING CONFUSED SEAS, AND SHIFT TO NORTHERLY CHOP LATE WED. AND THURS. INC. CLOUDINESS EXPECTED TODAY. SHOWERS AND THUNDERSTORMS EXPECTED WHEN NORTHER PASSES, CLEARING LATE WED. TIDES TO RISE ABOVE NORMAL TODAY AND COMMENCE FALLING BELOW NORM. WED.

THE FORECAST FROM 6 AM CST DECEMBER 10 TO 6 AM CST DECEMBER 11

WAVES: LOCATION Y: AV. 1.5'/MAX. 2.5' SE INC. GRADUALLY TO AV. 6.0'/MAX. 8.0' SE BY 6 AM WED.

WIND: SE 8/12 INC. GRADUALLY TO SSE 19/24 BY 6 AM WED.

WEATHER: PARTLY CLOUDY BECOMING CLOUDY WITH SHOWERS WED. MORN.

FORECAST RELIABILITY:* AVERAGE

THE OUTLOOK FROM 6 AM CST DECEMBER 11 CST 6 AM DECEMBER 12

WAVES: LOCATION Y: AV. 6.0'/ MAX 8.0' SE SHIFTING TO NNW LATE WED. MORN., AND DEC TO AV. 2'/ MAX. 3' NNE BY 6 AM THURSDAY.

WIND: SSE 19/24 SHIFTING TO NNW 25/31 GUSTS TO 40 LATE WED. MORN., SHIFTING TO NNE 25/31 BY 6 AM THURS.

WEATHER: CLOUDY, SHOWERS AND THUNDERSTORMS WED. MORN. BECOMING CLEAR BY THURS. MORN.

OUTLOOK RELIABILITY:* AVERAGE

TEMPERATURE DATA: TEMP AT Y AT 6 AM CST 62 °F

FORECASTED MAXIMUM TEMPERATURE AT Y DEC. 10 72 TO 75 °F

FORECASTED MINIMUM TEMPERATURE AT Y DEC. 11 48 TO 52 °F

TIDE DATA FOR "X" PASS H 7:30AM 1.6' L 6:53PM 0.2' 19 DEC 10 (PROVIDED ON REQUEST)

FIG. 7

3. Work can not be done late Tuesday or Wednesday. The boats can go into port and if boat or equipment maintenance is required it can be scheduled for Tuesday night or Wednesday morning.
4. Deep water work will not be efficient late Wednesday or Thursday because of north winds. Instead shallow water work should be planned, or work to

the south of topographic protection. Nine observations are possible between 3 and 6 PM behind topographic protection if it is sufficient to lower maximum waves to 2–3 feet.

The 48 hour forecasts have also been used in adjusting days off to coincide with unfavorable sea conditions. The savings achieved in this way can be illustrated as follows:

1. A crew operates in zone B (Figure 5) during January and takes 8 days off in every 30 days, without regard to sea conditions. From Figure 6 it can be seen that 730 gravity observations are expected during 30 days in January. Thus an average of 24.3 observations per day for the 8 days off would result in 195 observations lost during days-off.
2. On the other hand suppose the crew adjusts days-off to coincide with rough seas. Then a loss of only 91.3 observations is expected. This represents a difference of 104 observations or a little more than 4 days working time.

The difference results from the very few observations possible during rough seas as shown in Figure 2. The latter schedule adjusts days off to coincide with 1.5 days of 5 foot or higher waves; 4.5 days of 3 to 5 foot waves, and the remaining 2 days in 2 to 3 foot waves. It should be mentioned that a schedule of irregular days off based on forecasted sea conditions has not been followed as general policy when crews are within travelling distance of home. Adjustment of days-off is usually at the discretion of the party chief depending on the circumstances, and when forecasts are used in this way they not only represent a saving to the company but minimize the time the crew is idle at some remote coastal location. Also, it might be added that days-off coincident with rough seas does not necessarily imply days-off coincident with bad weather.

In the application of the 48 hour forecasts in daily planning, savings are smaller than in the case of advanced planning but can be achieved more frequently. Suppose that a party consisting of 2 gravity boats avoids 1 hour's unnecessary running time every three working days, through use of the data in the forecasts. Assuming a 21 day working month and a 10 hour working day, the saving is 14 hours or 1.4 boat days. Estimating $500 per day for the gravity boats, this totals $700. This estimate of savings possible through use of 48 hour forecasts indicates how modest improvements in efficiency pay-out the cost of wave forecasting services.

Other uses of the INDEX in connection with 48 hour forecasts may be outlines in less detail:

1. The survey area is sub-divided into zones that are completely exposed to all strong winds (i.e., points 25 miles off the coast), and zones that are protected by refraction or topography from certain high wave directions. Then during favorable seas only the unprotected zones are worked, and

during rough seas the zone protected from such seas is worked. The order of zones to be worked is planned from the forecasts.

2. Areas with poor bottom conditions are scheduled for work during calm or short period wave conditions.
3. Wind and astronomical tides are considered in planning shallow water work.

CONCLUSIONS

It has been indicated how the cost of the offshore gravity meter surveys can vary 50 percent depending on wave conditions, showing that careful planning for the wave conditions to be encountered is an important consideration in maintaining efficiency. Planning through use of the WAVE HEIGHT OPERATIONAL INDEX takes two forms. First, use of climatological wave studies for advanced planning. Here, large sums of money are tied up in a few major decisions. Second, use of the INDEX combined with 48 hour operational forecasts in field planning. Here, the savings are achieved through small sums of money involved in decisions made daily.

It is emphasized that the INDEX developed for the type of surveys studied herein required modification for application to operating conditions other than those outlined under the section "Description of Data."

No mention has been made of safety considerations in connection with weather and oceanographic planning. This also is worth consideration. Sea and weather forecasts enable offshore parties to avoid work in shallow water during the onset of northers, or line squalls, (avoiding running aground); to avoid being caught in fast moving, rapidly developing tropical storms; or to avoid unnecessary or ill-advised moves during hurricane periods. However, the benefits to be derived here are intangible and can not be assessed. Thus, emphasis is placed on the advantages in improved efficiency.

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CONTRIBUTIONS

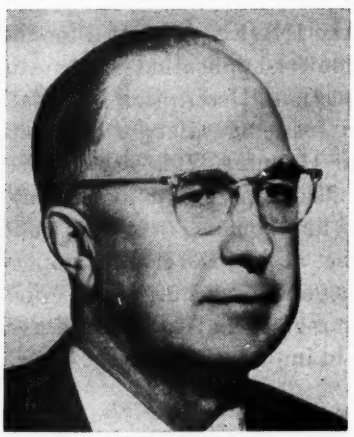
REFLECTION SEISMOGRAPH PROSPECTING—HOW IT STARTED*

WILLIAM SCHRIEVER†

Imagine the calamity that would be caused by a complete lack of the essential products supplied by our petroleum industry! Millions of automobiles and trucks would stay in their garages; farm tractors would not move over the fields, and the production of food would all but cease; our tremendous earth-moving machines would not disturb a single clod; busses would not take on passengers; many municipalities would be without water, heat, and electric power; crack trains, both passenger and freight, would not move; many industrial plants would have to close for lack of heat, power, and light; ocean liners would stay in their harbors; air transportation would not exist; our Army would be immobilized and our Naval vessels would stay at anchor.

Yet, only thirty years ago this failure in the supply of petroleum would have caused only inconveniences, but no real national disaster. This change from a horse and coal economy to a petroleum-natural-gas economy has taken place almost entirely since 1920.

The discovery of sufficient numbers of oil fields to supply the necessary huge quantities of petroleum and natural gas required scientific methods of exploration. Up until the early nineteen



John Clarence Karcher, '16ba, was a member of Pe-et, Sigma Tau, and was elected charter member of Phi Beta Kappa as an alumnus. Today he is president of Concho Petroleum Co. and a director of the Republic National Bank of Dallas. He has memberships in numerous professional and honorary groups.

twenties all scientific explorations were made by geologists who studied surface formations and prepared geologic maps which revealed surface indications of petroleum-bearing structures. As new oil fields became more difficult to find, new means of exploring for them were sought. Methods and instruments were required, with which it would be possible "to take a look" deep down below the surface of the earth. Such methods are called geophysical methods of exploration.

The first geophysical exploration for petroleum in the United States was made with an Eotvos torsion balance in 1922 by a crew working for the Amerada Petroleum Corporation under the direction

* Reprinted from *The Oklahoma Quarterly*, University of Oklahoma Association, Vol. 1, No. 4 (July 1952), pp. 27–30.

† Professor of Physics, Oklahoma University, Norman, Oklahoma.

of Dr. Everette DeGolyer, '11ba. In this same year Dr. DeGolyer also directed the work of a German refraction seismograph crew. The first salt-dome structures were discovered in 1924 in Fort Bend county, Texas; in the Nash area the torsion balance was successful, and the seismograph discovered the Orchard Dome. The Nash dome was the first oil field discovered by geophysical methods in the United States and perhaps in the entire world. The Orchard dome was the first oil field discovered by seismic methods in the United States—probably the first in the world; a refraction method with a mechanical seismograph was used.

More than a year before the first geophysical crew was working in Texas, several Oklahomans were testing their ideas concerning the reflection method of seismograph prospecting, the method which has been largely responsible for locating the new petroleum-bearing structures during the last twenty years. The first field tests of the reflection method were made on June 4, 1921. The first field party consisted of Dr. J. Clarence Karcher, '16ba, Dr. William P. Haseman, who was former head of the Department of Physics at the University of Oklahoma; Dr. Irving Perrine, former head of the Department of Geology at the University; and William C. "Cap" Kite, '16ba, a geologist and a former student of Dr. Perrine. Some years later Karcher developed reflection seismograph prospecting while he was associated with DeGolyer in the very successful Geophysical Research Corporation of Tulsa.

But we are getting ahead of our story of the birth of the reflection method of seismograph prospecting for oil. Karcher met Dr. Haseman, his former professor of physics at the University of Oklahoma, at the National Bureau of Standards in Washington in the summer of 1917. Since both were engaged in research on the sound ranging of big guns, and since both were familiar with the oil prospecting methods of that day, their conversations soon fell to the discussions of utilizing reflected sound waves (seismic waves) to determine the locations of oil-field structures. Opportunities to develop the method did not occur before Dr. Haseman was transferred to the University of Michigan for some special work on supersonic waves in water, and the discussions ceased until January of 1919, after Karcher had returned to Pennsylvania to continue graduate study.

At that time Haseman, who had returned to Oklahoma, began correspondence with Karcher concerning the possibility of using reflected seismic waves for prospecting purposes. Also at about this time, Karcher started the draft of a patent application concerning the method. Haseman soon invited Karcher to join a company which was to be organized to carry out investigations using reflected seismic waves. Karcher replied, expressing his great interest and suggesting that Dr. E. A. Eckhardt and Mr. Burton McCollum be invited. Eckhardt is now Vice President and Assistant Director of the Gulf Research and Development Co., concerned with exploration geophysics; McCollum is now President of the McCollum Exploration Company of Houston.

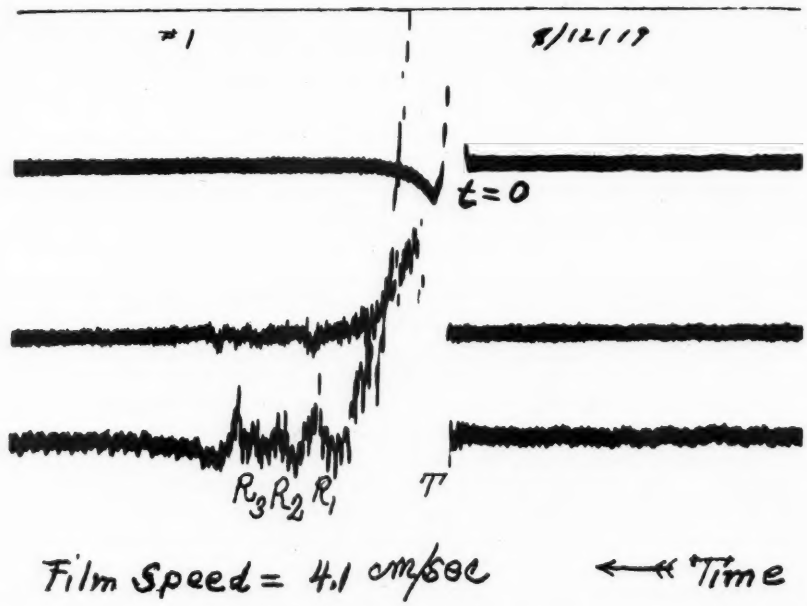
Early in the spring of 1919 Karcher conferred with Eckhardt and McCollum in Washington. After a long discussion of the method and the patent application, these three men decided to form a partnership for the purpose of pursuing the idea further. During the following summer. Dr. Karcher, after his graduate study at Pennsylvania, 1919–20, returned to the Bureau of Standards as physicist, and in his spare time assembled apparatus which enabled him to secure seismic records at the Bureau.

During the winter, Haseman again wrote to Karcher, this time proposing to organize a company for the purpose of exploiting their ideas concerning reflection seismograph surveys. Professor Haseman, in collaboration with Dr. D. W. Ohern, at one time Director of the Oklahoma Geological Survey, Irving Perrine, Mr. Frank Buttram, former member of the staff of the Survey, and others, organized the Geological Engineering Company in 1921. Karcher dissolved his partnership and joined this company. Messrs. McCollum and Eckhardt were retained as consultants, and were given stock in the company for their services.

During April of 1921, while Karcher was still in Washington, he designed and arranged for the purchase and construction of suitable apparatus for recording seismic reflections. He followed the apparatus to Oklahoma in May and in collaboration with Haseman completed the construction during that month.

The first field trip for testing the apparatus was made on June 4, 1921. This seismograph party was composed of Karcher, Haseman, Perrine, and Kite; it probably was the first seismograph explora-

tion party to operate in the United States. The first observations were made in a stream bed about one and one quarter miles due west of Belle Isle, a suburb in northwest Oklahoma City. Experimental field work was continued on June 6, 8, 9, 10, and forward. On June 16 a profile consisting of a series of seven shots spaced 100 feet apart and from 100 to 700 feet from the detector, was made. On the following day a similar profile extending from 300 to 1000 feet from the detector, yielded additional seismic records. These experiments were continued until early in July.



The world's first exploration seismograph record was made in a rock quarry north of the National Bureau of Standards in Washington, D. C., April 12, 1919, by Dr. Karcher. On the top trace of the tuning fork is shown the explosion instant at "$t=0$." On the lowest trace of a seismograph, T marks the instant of the arrival of the ground wave, and R_1, R_2, and R_3 record the arrival of reflected waves after explosion.

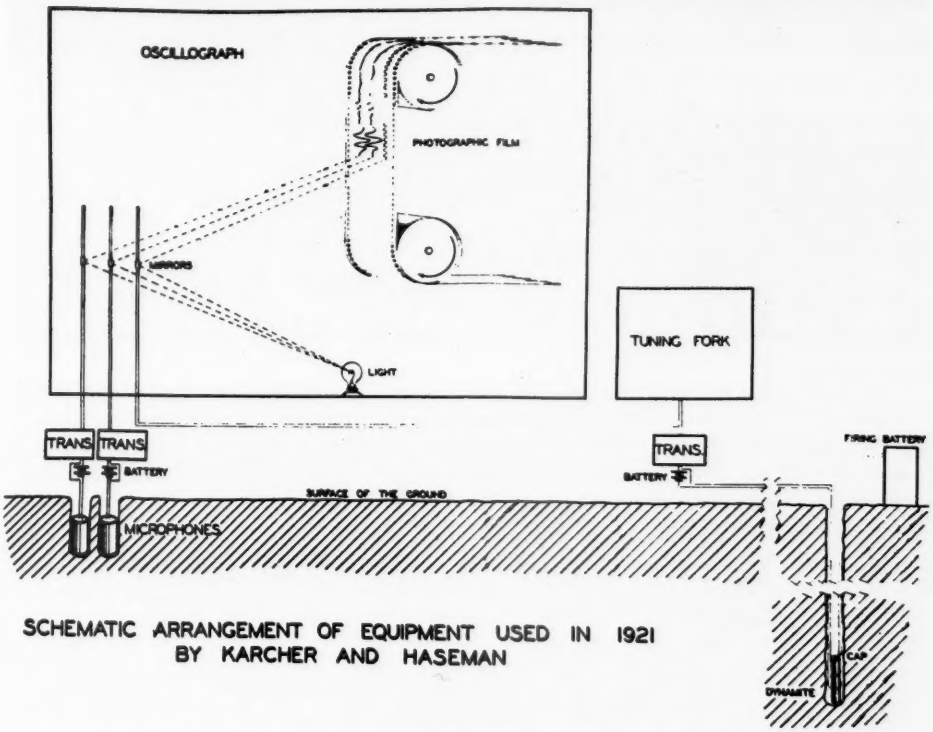
On July 14, 1921, a seismograph party consisting of Doctors Karcher, Haseman, Ohern, and Perrine went to the Arbuckle Mountains and, with the aid of dynamite explosions, determined the seismic wave velocity in the Hunton limestone to be 11,680 feet per second. During the next two days they measured the wave velocities in the Sylvan shale and the Viola limestone, and found them to be respectively 5,780 and 14,070 feet per second. These results showed that the contact between the Sylvan shale and the Viola limestone would make an excellent horizon for reflecting seismic waves.

Dr. Ohern then led the party to an area, known as Vines Branch, about seven miles north of Dougherty, Oklahoma, where a structural dome was known to exist. The caprock of this dome was the Viola limestone and this was overlain with Sylvan shale on the flanks of the dome. East of this dome the Viola plunged eastward and the depth of the shale increased as the distance from the dome increased. It was along this west-east line that the next experiments were conducted.

Along this line, nine shot-points were located at 100 foot intervals. At right angles to this line and 300 feet away were located the detector stations, one for each shot-point. This arrangement permitted a series of observations to be made where all conditions were constant except that the depth of the reflecting horizon (the Viola) increased with increasing distance from the dome. Records of well-defined reflections were obtained from the Viola limestone at varying depths up to 400 feet,

and Karcher was able to make calculations from the records which showed how the depth of the Viola changed with distance from the dome. During August of that year additional experiments were conducted near Oklahoma City.

On about September 1, 1921, a party consisting of Doctors Karcher and Haseman, and Mr. Reginald G. "Rex" Ryan (a geologist and former student at the University of Oklahoma) went to Ponca City, Oklahoma, to carry out seismic reflection experiments on the Newkirk anticline, a location some fifteen miles northeast of that city. Ohern, F. Park "Spot" Geyer, Chief Geologist of the Marland Oil Company, and his associate, Fritz L. Aurin, '14ba, '15ma, both former students of



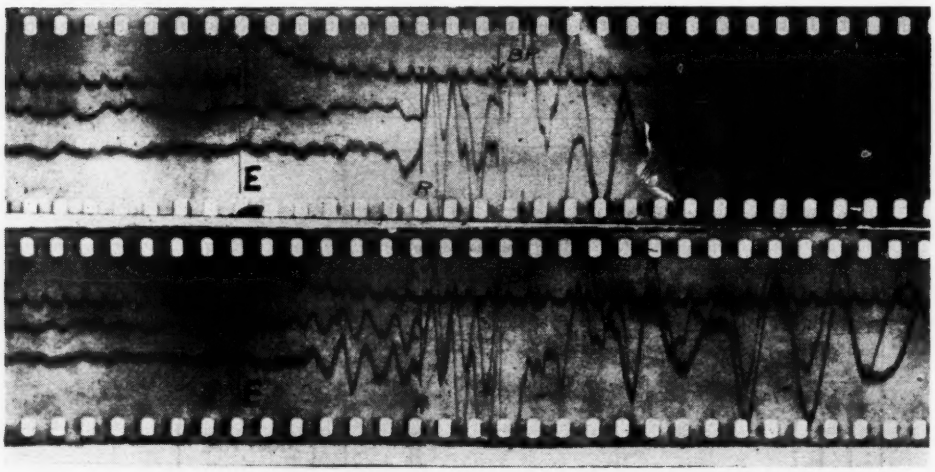
Schematic diagram of the apparatus used by Dr. William P. Haseman and Dr. J. Clarence Karcher in 1921. It was the world's first exploration reflection seismograph.

Perrine, assisted in locating suitable sites for the work. Many records showing identifiable reflections were obtained at various reflecting angles.

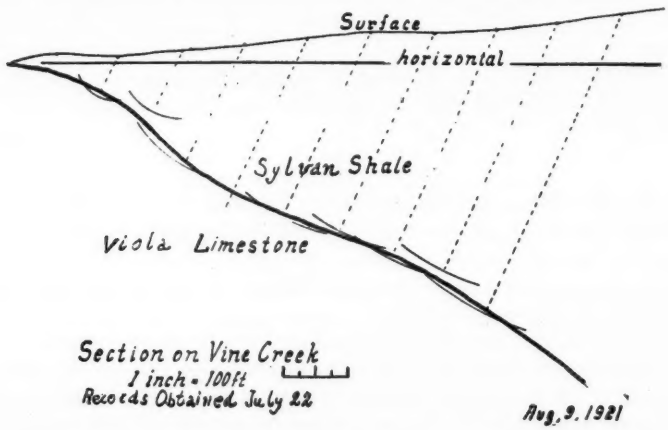
On September 13, a survey was begun for the Marland Oil Company in Section 28, Township 25 N, Range 4W. Work on the South Ponca structure was begun on October 14; on the Kildare area on October 18; and on the Deer Creek structure on October 26. It is interesting to note that by this time the explorers had developed the now well-known technique of placing dynamite well down in the subsoil and of filling the shot holes with water to increase the efficiency of production of seismic waves.

Funds for the experimental work were so meager that the program was abandoned about January 25, 1922. Karcher then returned to the National Bureau of Standards as Research Physicist. Later, in 1923, he accepted a position with the Western Electric Company in Chicago. Reflection seismograph prospecting for petroleum had not yet achieved any noteworthy results, but the

fundamental idea had been shown to be correct; only adequate financial resources were needed to develop the techniques into the most valuable of petroleum exploration methods. This development was soon to begin because another alumnus of the University of Oklahoma arranged for adequate financing of the project.



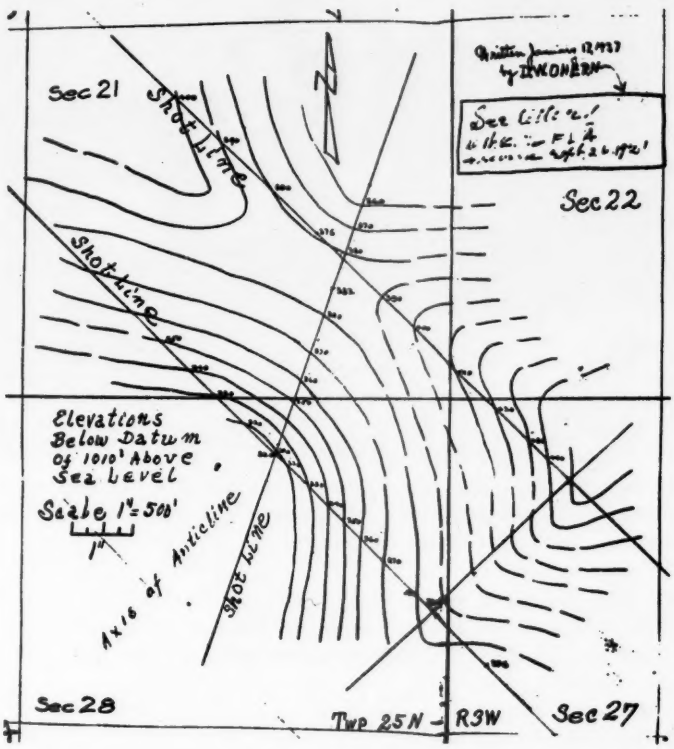
Two reflection seismograph records from those obtained during the survey for the Marland Oil Company. *E* indicates the time of dynamite explosion; *R* the time of arrival of reflected seismic wave; *BP* the arrival of the blast of explosion through the air. Top trace was supplied by the timing device (tuning fork): it served to record the explosion instant and to measure the time interval between the explosion and the arrival of the seismic wave at the dector (microphones). The other two traces are records of seismic waves, made by the two detectors. Tests made in Sept., 1921.



Depth of the Viola limestone at Vines Branch was measured with reflection seismograph on August 9, 1921—world's first reflection seismograph geologic section.

In 1925 Harold V. Bozell, a former professor of Electrical Engineering at the University and one of Karcher's former teachers, told Dr. DeGolyer of the seismograph work which Doctors Karcher and Haseman had been doing. DeGolyer, then Vice President of the Amerada Petroleum Corpora-

tion, was very much interested in the work and immediately arranged to interview Karcher in New York. Shortly thereafter Karcher was informed that the Amerada Petroleum Corporation would finance the necessary seismograph research to the extent of at least one hundred thousand dollars per year for a period of three years. Karcher resigned his position with the Western Electric Company and began work with Amerada on June 1, 1925. Shortly thereafter the Geophysical Research Corporation (now in Tulsa) was organized with DeGolyer as President and Karcher as Vice-President and General Manager. Within a few years the Geophysical Research Corporation became the largest operator of refraction seismograph equipment in the United States and one of the largest in the world. The refraction method was well adapted to the search for shallow salt domes in the Texas Gulf Coast area.



The world's first contour map of a geologic structure based on reflection seismograph data was prepared by F. L. Aurin, '14ba, '15ma, from data obtained near Ponca City by Doctors Karcher and Haseman for Marland Oil in Sept., 1921.

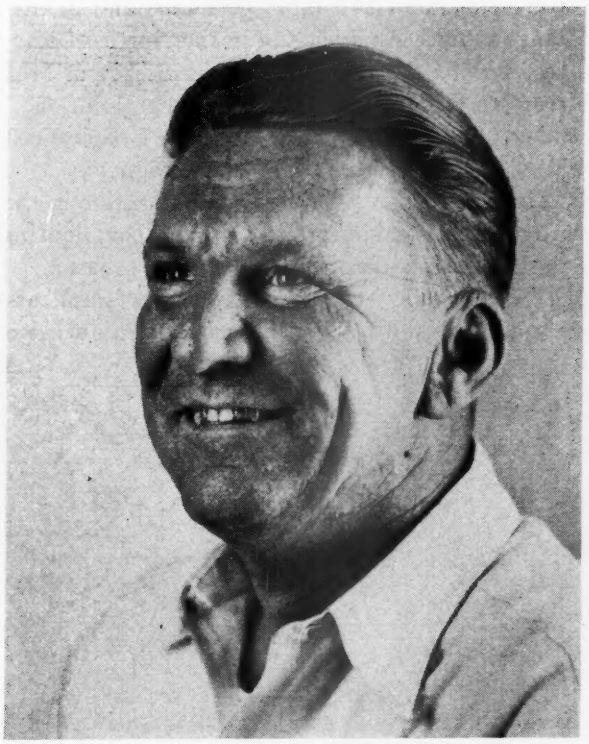
In 1929 Karcher sold his interest in G.R.C., and resigned his position there in 1930. He immediately organized another seismograph exploration company called Geophysical Service, Inc. This company specialized in reflection seismography and readily gained pre-eminence in this field. By 1938 it had thirty-four seismograph crews working throughout the United States, Canada, South America, and the Far East. On January 1, 1939 the activities of the Geophysical Service, Inc., were divided and placed under two corporations, one engaging in the oil business under the name of Coronado Corporation, and the other in the exploration business under the name of Geophysical Service, Incorporated. Karcher continued with management of the oil company. In 1941 he negotiated

The first exploration seismograph party to operate on a geologic structure in the United States: Oklahoma, August, 1921. The seismograph party consisted of Mr. Reginald G. "Rex" Ryan, Dr. William P. Haseman and Dr. J. Clarence Karcher.

the sale of both companies, the oil company being sold to the Stanolind Oil and Gas Company for a consideration of more than $5,000,000. The Geophysical Company was sold to four of its employees. Geophysical Service, Inc. is still one of the most important reflection seismograph petroleum exploration companies of the world.

Dr. Haseman's active life came to a close in 1932, but before he died, the reflection method of seismograph prospecting, which he and Dr. Karcher had labored so hard to bring into being, had become the leading method for petroleum exploration. Perhaps it should be called the Oklahoma Method of seismograph prospecting because it was developed in Oklahoma by Oklahomans nearly all of whom were alumni or former faculty members of the University of Oklahoma. Perrine, Ohern, Kite, and Buttram now live in Oklahoma City; Aurin resides in Fort Worth. Without doubt the success of the reflection method of seismograph prospecting has been far greater than could have been the wildest dreams of the men who observed the first seismic reflections in 1921.

MEMORIAL



JAMES CECIL JOHNSON (1907–1952)

James Cecil Johnson, 45, Senior Research Geophysicist of the Humble Oil & Refining Company, died at his home, 5005 Beach Street, Bellaire, Texas, after a heart attack the morning of August 12, 1952. The shock of his death was increased by the fact that it was completely unexpected and he had appeared to be feeling well on the preceding day.

J. C. Johnson, known to his friends far and wide as "Salty," was born June 30, 1907 in Yoakum, Texas, where he attended school and received the B.A. degree in English from the North Texas State Teachers' College, Denton in 1925. At an early age he became interested in amateur radio and his call, W5LS, was widely known in amateur radio circles. On many occasions he contributed unselfishly his time and experience in setting up and operating emergency radio communication networks in storm and flood damaged areas along the Gulf Coast.

In 1926 he served as instructor in the Gulf Radio School at New Orleans, Louisiana, and from 1926 to 1929 was employed by the Radio Corporation of America as a Marine Radio Operator. In 1929 he joined Humble Oil & Refining

Company as a seismograph operator and served for a number of years in the Gulf Coast region, in Venezuela and later in research and development activities.

From 1942 to 1945 he served as a Senior Radio Engineer for the Signal Corps engaged in the training of radar and radio personnel and in the installation of Signal Corps stations in South America and in the North African Theatre.

He is surved by his wife, the former Margaret Searcy of McKinney, Texas, and by two children, James Earl Johnson and Eleanor Johnson.

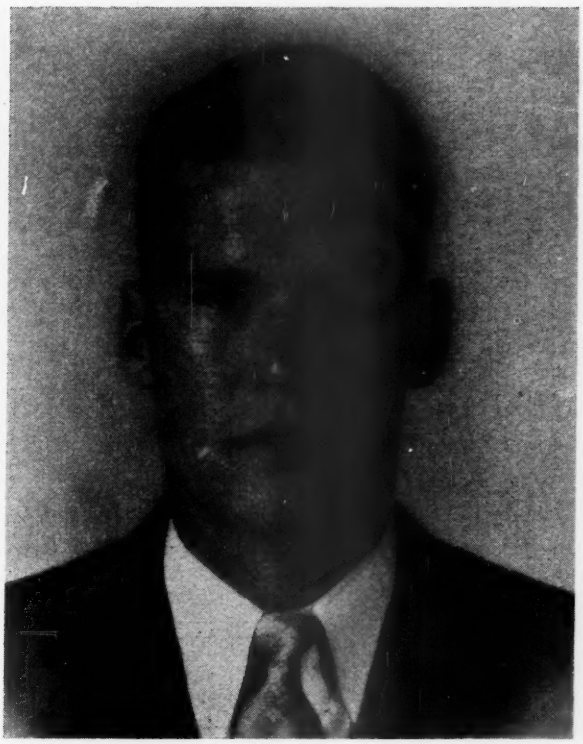
He was a member of the Society of Exploration Geophysicists, Institute of Radio Engineers, and the American Radio Relay League.

During the last few years of his life, he was very active in the Little League Baseball program, serving as trainer and coach, and contributing unselfishly of his time toward the success and improvement of this program.

Salty will long be remembered by his many friends and associates for his unfailing sense of humor, his untiring enthusiasm, and his sense of fair play.

W. M. RUST, JR.

MEMORIAL



JAKE MOON (1915–1952)

Jake Moon, Party Chief with Geophysical Service Incorporated, was killed in an explosion near Poza Rica, Veracruz, Mexico, on July 22, 1952. Moon was returning from Mexico City and was en route from Poza Rica to his party's camp 30 kilometers distant when the accident occurred. Approximately 6 kilometers from camp the narrow-gauge, gasoline-propelled rail car on which Moon was traveling exploded and instantly killed eight of the passengers, including Moon. It is believed that the reason for the accident was a gas explosion set off by the exhaust of the vehicle's motor. The gas came from an oil line, laid parallel to the tracks, which had been broken by a landslide caused by torrential rains falling for some time prior to the accident.

Moon's untimely death ended a career of 18 years' service with GSI which began in 1933. He was born in Garfield, Arkansas, on August 19, 1915 to Bennie H. and Lena Moon. The family later moved to Hutchinson, Kansas, where Jake Moon completed his public schooling. In September, 1933, he joined GSI as a Recorder Helper on a party under Cecil H. Green as Party Chief. With Green's

encouragement, Moon left the company in September, 1934 to attend Kansas State College at Manhattan, Kansas, where he completed a year's studies in Electrical Engineering and Geology.

Moon rejoined GSI in June, 1935 and served as Jr. Observer and later as Observer until 1945, when he was made a Computer. He was promoted to Party Chief in September, 1947 and stationed at Tampico, Mexico, after having served on a border crew in Mexico since March, 1944. Most of his work as a Party Chief continued in Mexico, except for an eight months' assignment in Canada in 1949 and 1950. Moon had seen previous foreign service for 16 months in the Magdalena Valley of Colombia in 1937 and 1938, as well as considerable domestic experience in the southern and mid-western areas of the U. S.

Moon was a member of the Society of Exploration Geophysicists and the American Geophysical Union. He was in the U. S. Naval Reserve from 1934 to 1938 and during World War II received an occupational deferment to continue his geophysical exploration work.

In 1938 Jake Moon married Ann McNamee of Rockdale, Texas. He is survived by his wife and son, Jon, age 11, of McAllen, Texas, and his parents, Mr. and Mrs. B. H. Moon of Hutchinson, Kansas.

Jake Moon was long a respected member of the GSI exploration team and was well liked by his fellow workers in Mexico. His loss is one which is keenly felt by his friends and associates everywhere.

J. W. THOMAS

MEMORIAL

JOSEPH AUDLEY SHARPE (1907–1952)

It is with deep regret and mixed emotions that these lines are written.

During the night of May 9th a heart attack ended the all too short life and professional career of Joseph Audley Sharpe.

To his many friends and associates he was known as Joe, Audley, and sometimes as Little Joe, but to all he will be remembered by that with which he has endowed us.

Although born in Axtell, Kansas March 7, 1907, most of his early life was spent in Arizona. It was at the University of Arizona that he received his first

scholastic honors by being elected to membership in Tau Beta Pi. During his last undergraduate year he worked at the Tucson Magnetic Observatory. Following graduation in 1928 he remained with the University as an instructor in the Physics Department. In 1930 he received a fellowship in Physics and Geology at the University of Wisconsin. At Madison he installed the university's seismological observatory while working on his Doctorate of Philosophy which he received in 1934. To conclude his formal education he spent the next year at M.I.T. as Rockefeller Foundation Fellow in Geophysics.

In 1935 Dr. Sharpe became associated with Western Geophysical Company as a research seismologist until 1937 when he became Chief Physicist and Laboratory Supervisor of Stanolind Oil and Gas Company in Tulsa.

Since 1945, when he terminated his association with Stanolind and assumed the office of Vice-president of Frost Geophysical Corporation, he was active in theoretical research as well as business management. At the time of his death he was Executive Vice-president of Frost Geophysical Corporation as well as President of the associated company at Frost Airborne Survey Corporation.

The prolific ingenuity of Dr. Sharpe resulted in his many disclosures of inventions relating to the field of geophysics and geophysical instrumentation. Of his many published papers it is appropriate that appearing in this issue is his final paper as given at the Pacific Coast Regional Meeting.

Dr. Sharpe's avocation was his vocation thus he enjoyed toying with bits picked up in the publications of the various technical societies in which he was a member. This rather impressive list includes: The American Physical Society, American Mathematical Society, American Geophysical Union, Seismological Society of America, American Institute of Mining and Metallurgical Engineers, American Association of Petroleum Geologists (Research Committee 1943–46), Society of Exploration Geophysicists (Editor *Geophysics* 1942–45), Tulsa Geological Society (Council 1949), and the Geophysical Society of Tulsa (Executive Committee 1947).

He is survived by his wife, Cecile, and two sons, Norman and Conrad, all of whom are presently remaining at their home in Tulsa.

Thus it is with deep regret that I lose a friend and respected counselor. I regret that his chapter has ended, but I am gratefully glad to receive the benefits of his scientific endowment to all of us.

JOHN H. HIDY

MEMORIAL

CLAYTON REEVES LOWE (1909–1952)

Clayton Reeves Lowe, Vice President and Assistant General Manager of Independent Exploration Company, died very suddenly from a heart attack in his home at 3131 Castlewood Street, Houston, Texas on the night of May 16, 1952. He had just returned from a business trip to Corpus Christi and San Antonio, Texas some few hours before his death. His untimely passing was indeed a great shock and a great loss to his family and many friends in the Geophysical Industry.

Clayton was born on February 18, 1909 in Shreveport, Louisiana, the son of J. H. Lowe and Eleanor C. Lowe. He attended Elementary and High School at St. Johns in Shreveport, Louisiana. After graduating from High School he entered Washington and Lee University at Lexington, Virginia, and attended two years. He then transferred to Louisiana State University at Baton Rouge, Louisiana where he received a B.S. degree in Civil Engineering in June 1931.

Shortly after graduation from college Clayton was employed by the Louisiana Highway Department as a Surveyor. In 1933 he went to work for the U. S. War Department as a Surveyor at Barksdale Field, Shreveport, Louisiana. On January 19, 1935 he joined the Independent Exploration Company as a Surveyor on one of its seismograph crews located at Pecos, Texas. By hard conscientious work Clayton moved up through the ranks and on September 11, 1950 was made Vice President of Independent Exploration Company.

On May 12, 1941 Clayton married Ann Mabel Flowers of Shreveport, Louisiana. He is survived by his widow, two daughters, Diana Kaye and Noel Ann Lowe, and one son, Warren Clayton Lowe, residents of Houston, and his mother, father, and two brothers, residents of Shreveport, Louisiana.

Clayton was a member of the Society of Exploration Geophysicists including the Houston Section, the Houston Geological Society, Sigma Nu Social Fraternity, and the Petroleum Club of Shreveport, Louisiana.

Clayton Lowe will always be remembered by those who came in contact with him as being a very reliable and efficient business associate. In his passing his family has lost a devoted father and husband and his friends a great friend.

CURTIS P. HARKINS

Houston, Texas
June 19, 1952

PATENTS

O. F. RITZMANN*

ELECTRICAL PROSPECTING

U. S. No. 2,599,688. A. A. Brant. Iss. 6/10/52. App. 1/17/51. Assign. Newmont Mining Corp.

Resistivity Method for Determining Ore Continuity. A method of testing whether two apparently-isolated ore bodies are connected by passing a current between one ore body and a remote electrode and observing the potential between the other ore body and another remote electrode.

GRAVIMETRIC PROSPECTING

U. S. No. 2,595,092. W. D. Mounce. Iss. 4/29/52. App. 5/19/47. Assign. Standard Oil Development Co.

Method and Apparatus for Underwater Gravity Surveying. A condenser-type gravimeter in which the varying-frequency signal is combined with signal of standard frequency and the difference frequency converted to pulses which are counted over a known time interval.

MAGNETIC PROSPECTING

U. S. No. 2,590,979. E. G. Kogbetliantz. Iss. 4/1/52. App. 5/6/48.

System for Measuring Magnetic Fields. A magnetometer having two rhombic magnets individually pivoted at its center of gravity on the same axis and the distance between them adjustable to a critical value and the angle between their magnetic axes observed.

U. S. No. 2,596,638. A. J. Arvela. Iss. 5/13/52. App. 6/11/47 and 5/17/48.

Magnetic Variometer. A suspended-needle type of magnetic variometer in which the magnetized needle is mounted at the midpoint of a horizontal fiber and has a depending pointer which is brought opposite an index point by current in a coil adjacent to the needle.

U. S. No. 2,597,149. T. Kahan. Iss. 5/20/52. App. 8/5/48 and 3/29/49. Assign. Office National d'Etudes et de Recherches Aeronautiques.

Ultrahigh-Frequency Magnetometer. A magnetometer having a bar of magnetic material influenced by the field and extending into a wave guide which is excited by a uhf oscillator, the variation in coefficient of reflection of the bar being observed as the magnetic field varies.

U. S. No. No. 2,598,284, G. Muffly. Iss. 5/27/52. App. 6/23/47 and 5/3/51. Assign. Gulf Research & Development Co.

Apparatus for Measuring Intensity of Magnetic Fields. A stabilized flux-gate magnetometer in which the output of the sensitive element is modulated by a coil energized from an earth inductor rotating on the axis of the element and in which the orienting servomotors are controlled by the phase of the output modulation.

U. S. No. 2,598,285. G. Muffly. Iss. 5/27/52. App. 6/23/47 and 5/3/51. Assign. Gulf Research & Development Co.

Method and Apparatus for Measuring Intensity of Magnetic Fields. A stabilized flux-gate magnetometer whose instantaneous axis of sensitivity is made to nutate about the principal axis by progressively saturating a symmetrical configuration of magnetic vanes about one end of the element and in which the orienting servomotors are controlled by the phase of the output modulation.

* Gulf Oil Corporation, Patent Department

U. S. No. 2,598,697. H. Jensen. Iss. 6/3/52. App. 7/2/46.

Method and Apparatus for Conducting Geophysical Surveys. A system of aeromagnetic surveying in which the magnetometer record is periodically edge-marked with a serial number, the terrain beneath the aircraft photographed and also marked with the same serial number, and a photograph taken of the altimeter reading showing also the magnetometer control dial settings and the same serial number.

U. S. No. 2,598,698. H. Jensen. Iss. 6/3/52. App. 7/2/46.

Method and Apparatus for Magnetic Explorations. A system of aeromagnetic surveying in which the magnetometer record is photographically superimposed on a strip photograph of the terrain below the aircraft, the strip chart being periodically marked with a serial number and a record of the magnetometer sensitivity and base line.

U. S. No. 2,599,550. R. Fraser. Iss. 6/10/52. App. 4/27/49.

Fluxmeter and Probe Therefor. A fluxmeter probe having two metals forming two arms of a Wheatstone bridge circuit, the resistance of one metal being sensitive to magnetic field and the other being insensitive to the field but providing temperature compensation.

U. S. No. 2,599,687. A. A. Brant. Iss. 6/10/52. App. 11/10/48 and 4/23/49. Assign. Geophysical Exploration Co.

Drill Hole Magnetometer Apparatus. A borehole magnetometer having a flux valve pendulously suspended in gimbals so as to measure the vertical component of magnetic field.

SEISMIC PROSPECTING

U. S. No. 2,591,177. W. H. Mayne. Iss. 4/1/52. App. 12/2/49. Assign. Olive S. Petty.

Seismic Surveying. A system for permitting the checking of seismometer polarity by having a battery connected in series with the seismometer coil and an opposing battery in series with the input amplifier, seismometer polarity being remotely determinable by connecting a meter to the line.

U. S. No. 2,591,192. J. O. Parr, Jr. Iss. 4/1/52. App. 11/29/49. Assign. Olive S. Petty.

Seismic Surveying. A system for permitting the checking of seismometer polarity by having a rectifier connected in parallel with each seismometer coil, the polarity of the rectifier being remotely determinable by the application of a battery voltage to the seismometer line.

U. S. No. 2,591,637. A. E. Tilley. Iss. 4/1/52. App. 4/29/49. Assign. Phillips Petroleum Co.

Automatic Volume Control Circuit. An avc circuit for seismograph amplifiers having a condenser discharge type of expander with a signal-controlled tube paralleling the discharging resistor so that the increase in gain will be accelerated when the signal level becomes low.

U. S. No. 2,591,795. J. D. Eisler. Iss. 4/8/52. App. 11/15/49. Assign. Stanolind Oil and Gas Co.

Vibration Detector. A moving-coil electromagnetic seismometer having an annular magnet with a central hollow pole piece and with a helical spring extending through the central pole piece to vertically support the suspended coil.

U. S. No. 2,592,780. J. P. Woods. Iss. 4/15/52. App. 6/18/47. Assign. The Atlantic Refining Co.

Seismic Method and Apparatus. An underwater seismometer having a torpedo-shaped case with a transducer mounted on bearings which permit rotation on a longitudinal axis and cable terminals on each end of the case.

U. S. No. 2,593,052. R. G. Piety and M. E. Thomas. Iss. 4/15/52. App. 5/17/48. Assign. Phillips Petroleum Co.

Seismometer. A suspended-magnet magnetic-bridge type of seismometer in which the moving magnet has protrusions from which the flux crosses the air gap to the cores which are closely spaced opposite the protrusions.

U. S. No. 2,594,219. W. Roth and J. Ohman. Iss. 4/22/52. App. 12/21/49. Assign. Geovision Inc.

Apparatus for Geophysical Display. A system for generating the necessary scanning potential to trace an equal-time curve on a c-r tube for displaying seismic reflections having two modulators which modulate a sine wave in accordance with sinh (kt) and cosh (kt-1).

U. S. No. 2,594,702. S. W. Woodard. Iss. 4/29/52. App. 8/30/48. Assign. Dale Service Corp.

Retrievable Marine Marker. A marine marker having a geophone which initiates operation of motor-driven strikers to produce sound signals when activated by a seismic wave and which releases a float when a coded series of seismic impulses is received.

U. S. No. 2,594,767. R. P. Green. Iss. 4/29/52. App. 11/1/43 and 2/8/46. Assign. Engineering Laboratories, Inc.

Method of Seismic Surveying. A method of analyzing a seismogram by recording it on a magnetic tape which is subsequently repeatedly reproduced at various speeds and the waves analyzed with a rotating mirror.

U. S. No. 2,596,463. A. J. Barthelmes. Iss. 5/13/52. App. 5/8/46. Assign. Seismograph Service Corp.

Method for Determining Subsurface Geological Structure by Seismic Surveying Employing Refraction Shooting. A continuous profile refraction method of seismic shooting in which refraction shots are made in both directions to the spread which is moved along the profile.

U. S. No. 2,599,064. J. P. Minton. Iss. 6/3/52. App. 7/22/46. Assign. Socony-Vacuum Oil Co., Inc.

Seismic Prospecting. A seismograph-mixing system in which interchannel coupling is through a band-pass filter and asymmetric mixing tube so that signals of selected frequencies may be used for mixing.

U. S. No. 2,599,245. R. S. Finn. Iss. 6/3/52. App. 6/27/47. Assign. Seismograph Service Corp.

Method and Apparatus for Seismic Prospecting. A method of marine seismic shooting in which an auxiliary explosive charge is simultaneously detonated between the main charge and the surface so as to produce a gas escape path from the main charge to the surface.

U. S. No. 2,599,775. G. Peterson. Iss. 6/10/52. App. 7/1/48. Assign. Phillips Petroleum Co.

Electrostatic Seismometer. A variable capacitance type of high impedance seismometer in which a high ratio of variable to fixed capacitance is attained by having a stack of spaced ring-shaped plates forming one side of the condenser and a suspended stack of equally-spaced discs forming the other side of the condenser, the outer edges of the discs being opposite the inner edges of the rings.

U. S. No. 2,600,051. C. H. Fay and T. J. Tvedt. Iss. 6/10/52. App. 12/20/49. Assign. Shell Development Co.

Seismograph Amplifier Control. A seismograph avc system in which the signal passes through two Wheatstone bridges between successive stages of amplification and the bridges each contain in one arm a non-linear resistance whose resistance is controlled by high frequency a-c controlled from the output signal.

U. S. No. 2,600,967. A. A. Chernosky. Iss. 6/17/52. App. 6/5/48. Assign. Standard Oil Development Co.

Low-Frequency Vibrational Pickup. A moving-coil electrodynamic seismometer in which sag of the suspension spring due to the weight of the suspended coil is overcome by passing a d-c from a high impedance circuit through the coil.

U. S. No. 2,601,522. C. A. Heiland and M. T. Murray. Iss. 6/24/52. App. 2/28/46.

Method for Geophysical Exploration. A method of seismic shooting in which a shaped charge is located in the earth at such an angle that its jet is in the direction of the critical refraction ray of an underlying formation.

U. S. No. 2,601,543. K. W. McLoad. Iss. 6/24/52. App. 9/12/49. Assign. Socony-Vacuum Oil Co., Inc.

Double Coil Cable Geophone. A moving coil seismometer which may be inserted in a cable for marine seismic operations and whose internal structure is mounted on bearings and oriented by gravity and having a coil in an air gap at the top of the structure and another coil in another air gap at the bottom of the structure, the coils being connected in series aiding for seismic impulses but in opposition for magnetic disturbances.

WELL LOGGING

U. S. No. 2,590,873. S. Krasnow and L. F. Curtiss. Iss. 4/1/52. App. 10/24/39. Assign. Schlumberger Well Surveying Corp.

Method and Apparatus for Measuring Radioactivity. A radioactivity indicator having an ionization chamber connected to an oscillator so that changes in the impedance of the chamber will change the oscillator frequency which is observed.

U. S. No. 2,590,874. S. Krasnow and L. F. Curtiss. Iss. 4/1/52. App. 7/24/42. Assign. Schlumberger Well Surveying Corp.

Multiple Element Radioactive Ray Recording. A radioactivity-logging system in which a number of detectors are used having different radiation-response characteristics and their responses compared.

U. S. No. 2,590,982. A. B. Long. Iss. 4/1/52. App. 9/20/46. Assign. Sun Oil Co.

Well Logging Apparatus. A self-contained well-logging apparatus having a moving chart on which is recorded the well liquid pressure, temperature, and viscosity, the latter being determined at intervals by successively dropping magnetized beads through the liquid and recording their time of fall.

U. S. No. 2,592,101. C. B. Aiken. Iss. 4/8/52. App. 2/4/42 and 10/10/45. Assign. Schlumberger Well Surveying Corp.

Electrical Logging. A dielectric-constant logging system in which two electrodes are in one arm of a high-frequency bridge circuit and the phase difference between the voltage across the electrodes and the voltage across a pure resistance is indicated.

U. S. No. 2,592,125. H.-G. Doll. Iss. 4/8/52. App. 11/18/49. Assign. Schlumberger Well Surveying Corp.

Method and Apparatus for Logging Static Spontaneous Potentials in Wells. A system for measuring the SP log in which current is introduced at auxiliary electrodes above and below the measuring electrode so as to produce zero potential difference between the auxiliary electrodes and the measuring electrode, and observing the potential difference between the measuring electrode and a remote ground.

U. S. No. 2,592,434. S. Krasnow. Iss. 4/8/52. App. 4/10/42. Assign. Schlumberger Well Surveying Corp.

Radioactive Marker. A radioactive bullet whose jacket may be permanently magnetized and which contains radioactive material, the bullet having a plug at its base which is transparent to the radiation.

U. S. No. 2,593,285. C. H. Fay and M. Stephenson. Iss. 4/15/52. App. 4/26/48. Assign. Shell Development Co.

Oil Well Flowmeter. A subsurface flowmeter having an impeller in shock-mounted bearings and with a magnet on its shaft, the indicating mechanism being in a sealed case and driven by a follower magnet.

U. S. No. 2,595,042. M. R. J. Wyllie. Iss. 4/29/52. App. 3/23/50. Assign. Gulf Research & Development Co.

Nonpolarizing Electrode for Electric Logging of Boreholes. A porous-cup type of non-polarizing electrode for use in electric logging in which the pressure of the internal electrolyte is maintained slightly higher than the pressure of external borehole fluid by a hydrostatic pressure-exchange device.

U. S. No. 2,595,241. R. W. Goble. Iss. 5/6/52. App. 8/1/47. Assign. Eastman Oil Well Survey Co.

Method and Apparatus for Measuring the Cross Sectional Area of Well Bores by Supersonic Waves. A well calipering device having a sound wave generator and receiver which is rotated to transmit supersonic pulses in various radial directions and which measures the average transit time of the pulse from the generator to the well wall and return to the receiver.

U. S. No. 2,596,023. R. W. Goble and G. Jackson. Iss. 5/6/52. App. 12/16/44. Assign. Eastman Oil Well Survey Co.

Audio Caliper Device. A well calipering device having a number of sound wave generators arranged to transmit and receive supersonic pulses in different radial directions and measuring the transit time of a pulse from the generator to the borehole wall and return.

U. S. No. 2,596,024. R. W. Goble and G. Jackson. Iss. 5/6/52. App. 12/16/44 and 10/9/50. Assign. Eastman Oil Well Survey Co.

Audio Caliper Device. A well calipering device having a number of sound wave generators arranged to transmit and receive supersonic pulses in different radial directions and measuring the average transit time of the various pulses so as to indicate the average diameter of the well.

U. S. No. 2,596,437. G. H. Rohback, R. A. Stoner, M. Macaulay and W. T. Cardwell, Jr. Iss. 5/13/52. App. 2/16/51. Assign. California Research Corp.

Method and Apparatus for Detecting Fluid Movement in Well Bores. A subsurface flowmeter having a pair of electrodes in separate passages through the meter and a motor-driven valve which directs the flow alternately through the passages, the variation in potential difference between the electrodes being observed.

U. S. No. 2,598,520. H. J. Eastman. Iss. 5/27/52. App. 4/19/46. Assign. Eastman Oil Well Survey Co.

Borehole Temperature Recorder. A photographically-recording borehole thermometer having a dial and pointer, the unit being interchangeable with a well-surveying apparatus so as to use the same recording camera.

U. S. No. 2,598,551. G. Jackson. Iss. 5/27/52. App. 5/6/46. Assign. Eastman Oil Well Survey Co.

Temperature Indicating Unit. A bimetallic thermometer unit with a transparent scale which can

be mounted in a photographically-recording well-surveying apparatus so as to indicate on the same record.

U. S. No. 2,599,112. W. F. Krueger. Iss. 6/3/52. App. 10/7/47. Assign. Sperry-Sun Well Surveying Co.

Apparatus for Determining the Time of Descent of Instruments within Boreholes. A device for marking the record of a well-surveying apparatus when it strikes bottom and having a vertically-suspended mass carrying a pin which strikes the record when downward movement of the apparatus is arrested.

U. S. No. 2,599,413. P. P. Reichertz. Iss. 6/3/52. App. 1/18/50. Assign. Socony-Vacuum Oil Co., Inc.

Drilling Mud Resistivity Meter. A four-electrode mud-conductivity measuring device in which a-c is passed between the current electrodes and part of the a-c balanced against the potential across the potential electrodes, with the unbalance amplified and indicated.

U. S. No. 2,599,687. A. A. Brant. Iss. 6/10/52. App. 11/10/48 and 4/23/49. Assign. Geophysical Exploration Co.

Drill Hole Magnetometer Apparatus. See MAGNETIC PROSPECTING.

U. S. No. 2,599,975. P. G. Carpenter. Iss. 6/10/52. App. 11/8/48. Assign. Phillips Petroleum Co.

Apparatus and Method for Measuring the Velocity of Fluids. A flow meter in which a foreign liquid is introduced into the flowing fluid and the outgoing fluid is compared with the incoming fluid by means of photocells or other detecting devices.

MISCELLANEOUS

U. S. No. 2,591,698. J. E. Henry. Iss. 4/8/52. App. 1/15/47.

Shoran Mechanical Straight-Line Computer. A flight computer using Shoran signals having a scale model of the ground stations with pivoted rods which are moved to have a length proportional to the distance indications and which engage a pin representing the airplane, the pin being movable along a straight track and indicating deviation signals to the pilot.

U. S. No. 2,591,737. R. E. Souther, Jr. Iss. 4/8/52. App. 11/28/50. Assign. National Lead Co.

Detection of Oil in Mud-Laden Well Drilling Fluids. A method of detecting oil in drilling mud by subjecting the mud to steam distillation and testing the vapor or condensate for the presence of oil.

U. S. No. 2,592,378. P. E. Chaney and W. E. Barnes. Iss. 4/8/52. App. 10/30/48. Assign. Sun Oil Co.

Apparatus for Determining the Zone of Lost Circulation of Drilling Mud. A device which may be mounted on the end of the drill pipe and having an impeller wheel with vibration-generating hammers which is actuated when there is return of circulation at the level of the end of the drill pipe.

U. S. No. 2,594,749. K. Ehrat and V. Milliquet. Iss. 4/29/52. App. 12/13/44 and 12/10/45. Assign. "Patelhold" Patentverwertungs- & Elektro-Holding A.-G.

Mechanical Vibration System. An electrically-driven tuning fork having four symmetrically-vibrating tines so that vibration stresses at their junction are compensated and the frequency effect of the mounting eliminated.

U. S. No. 2,595,578. R. E. Hartline and R. P. Murphy. Iss. 5/6/52. App. 12/30/49. Assign. Stanolind Oil and Gas Co.

Fluid Ingress Location in Wells. A method of well testing in which the well is produced to reduce

bottom-hole pressure, then brine introduced into the annulus to partially restore normal pressure, and after the brine has reached bottom running a fluid-resistivity log to detect changes in the brine caused by formation fluids entering the well.

U. S. No. 2,595,610. D. Silverman and R. E. Hartline. Iss. 5/6/52. App. 12/30/49. Assign. Stanolind Oil and Gas Co.

Fluid Ingress Location in Wells. A method of locating levels of fluid entry into a pumping well by producing it at a rate such that bottom-hole pressure is less than static, introducing into the annular space a conditioning water of different electrical resistivity than the formation water, and lowering an electrode down the annular space to detect contamination of the conditioning water.

SELECTED LIST OF U. S. PATENTS ISSUED DURING THE SECOND QUARTER OF 1952.

Patent No.	*Subject*	*Patent No.*	*Subject*	*Patent No.*	*Subject*
2,590,837	16	2,591,996	484	2,593,000	428
2,590,867	308	2,592,009	428	2,593,014	16
2,590,873[a]	304, 308	2,592,014	312	2,593,052[a]	376
2,590,874[a]	304	2,592,101[a]	116	2,593,062	200
2,590,882	136	2,592,115	308	2,593,070	216
2,590,925	308	2,592,125[a]	116	2,593,071	316
2,590,930	520	2,592,134	140	2,593,169	288
2,590,979[a]	232	2,592,135	140	2,593,172	200
2,590,982[a]	460, 288, 496	2,592,176	16	2,593,285[a]	148,144
2,591,045	324	2,592,222	140	2,593,313	168
2,591,070	224	2,592,223	428	2,593,339	484
2,591,074	444	2,592,295	520	2,593,407	236
2,591,075	200	2,592,378[a]	144	2,593,432	312
2,591,177[a]	360	2,592,402	104	2,593,473	200
2,591,192[a]	360	2,592,416	308	2,593,485	312
2,591,195	148	2,592,422	520	2,593,493	428
2,591,233	104	2,592,434[a]	304, 220	2,593,509	16
2,591,255	288	2,592,459	316	2,593,587	200
2,591,319	48	2,592,567	324	2,593,616	416
2,591,478	148	2,592,569	288	2,593,620	48
2,591,615	520	2,592,572	324	2,593,633	484
2,591,637[a]	372	2,592,582	16	2,593,694	12
2,591,698[a]	68, 312	2,592,583	324	2,593,695	12
2,591,731	316	2,592,643	16	2,593,698	12
2,591,737[a]	252	2,592,652	224	2,593,865	140
2,591,759	168	2,592,703	484	2,593,866	48
2,591,760	168	2,592,719	316	2,593,906	288
2,591,761	168	2,592,721	484	2,594,029	84
2,591,762	168	2,592,744	200	2,594,163	188
2,591,795[a]	376	2,592,777	316	2,594,212	308
2,591,808	168	2,592,780[a]	376	2,594,219[a]	360
2,591,856	316	2,592,834	168	2,594,292	392
2,591,908	312	2,592,855	316	2,594,317	316
2,591,921	4	2,592,868	448	2,594,332	140
2,591,938	16	2,592,929	200	2,594,334	416

[a] Abstracted on preceding pages of this issue.

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2,594,668	148
2,594,702[a]	360, 376
2,594,731	224, 68
2,594,749[a]	368
2,594,767[a]	360
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2,594,887	68
2,594,893	224
2,594,934	224
2,594,947	228
2,594,948	484
2,594,970	308
2,594,989	228
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2,595,205	16, 68, 444
2,595,241[a]	520
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2,595,578[a]	524
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2,595,622	308
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2,595,791	484
2,595,868	16
2,595,876	316
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2,595,960	136
2,596,019	160
2,596,023[a]	520
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2,596,048	492
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2,596,271	288
2,596,305	324
2,596,352	412
2,596,437[a]	148
2,596,446	324
2,596,463[a]	360
2,596,494	484
2,596,500	308
2,596,529	492
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2,597,125	216
2,597,135	216
2,597,138	496
2,597,149[a]	232
2,597,151	16
2,597,199	108
2,597,297	316
2,597,315	68, 312
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2,597,349	312
2,597,362	460
2,597,409	48
2,597,520	372
2,597,531	16
2,597,535	308
2,597,607	316
2,597,636	316
2,597,784	16
2,597,862	316
2,597,866	68
2,597,892	16
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2,597,939	460
2,598,096	444
2,598,132	12, 224
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2,598,237	372
2,598,250	68
2,598,252	132
2,598,267	460
2,598,284[a]	232
2,598,285[a]	232
2,598,290	312
2,598,312	68
2,598,355	444
2,598,520[a]	452, 460, 520
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2,598,551[a]	452, 460, 520
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2,598,668	484
2,598,672	16, 180
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2,598,835	200
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2,599,036	76, 380
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2,599,112[a]	520
2,599,124	216
2,599,156	308
2,599,166	308
2,599,245[a]	360, 136
2,599,288	16
2,599,352	308
2,599,405	392
2,599,413[a]	116
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2,599,550[a]	232	2,600,193	316	2,600,865	444
2,599,578	428	2,600,209	16	2,600,967[a]	376
2,599,586	108, 436	2,600,255	316	2,601,028	460
2,599,588	324	2,600,264	68	2,601,097	236
2,599,661	160	2,600,271	288	2,601,245	436
2,599,687[a]	220, 232	2,600,324	288	2,601,259	428
2,599,688[a]	124	2,600,335	316	2,601,272	168
2,599,775[a]	376	2,600,336	100, 324	2,601,300	484
2,599,889	68, 312	2,600,341	200	2,601,327	420
2,599,922	168, 308	S.N. 567,394	216	2,601,334	308
2,599,975[a]	148	2,600,396	188	2,601,508	460
2,600,029	428	2,600,423	372	2,601,522[a]	360, 136
2,600,046	224	2,600,484	312, 444	2,601,543[a]	376
2,600,051[a]	372	2,600,546	484	2,601,583	308
2,600,125	80, 84	2,600,644	216	2,601,637	308
2,600,158	168	2,600,701	428	2,601,678	484
2,600,159	68	2,600,822	324		
2,600,173	524	2,600,828	16		

NOMOGRAMS

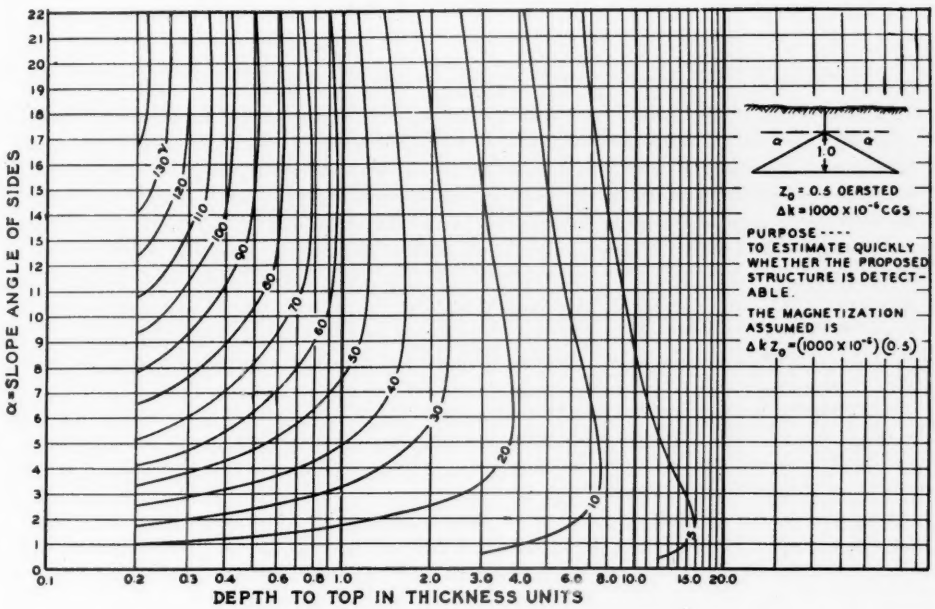
CHART TO ESTIMATE MAGNITUDE OF MAGNETIC ANOMALIES

Both in the planning and interpretation of magnetic surveys it is useful to be able to estimate quickly how large in gamma amplitude and areal extent will be the anomaly for a particular type of structure. The elongated anticline with core of basement rocks of higher magnetization is a common type of structure hunted.

The chart presented here allows a rapid determination of the theoretical maximum anomaly in the VERTICAL component (ΔZ) of the earth's magnetic field produced by a wide variety of elongated anticlinal shaped masses of magnetization contrast ($\Delta k Z_0$), lying in a magnetizing field which is vertical (Z_0). For areas where the magnetizing field is inclined the anomalies show marked changes in shape but the gamma amplitudes are substantially the same. Further, anomalies in TOTAL intensity also show substantially the same amplitude although the shapes change with magnetic latitude. The chart thus allows one to estimate gamma amplitude for this type of anomalous mass over the entire range of magnetizing field intensities, and at any magnetic latitude.

For example, suppose elongated folds with basement cores are expected in an area. What is the maximum anomaly due to an anticlinal core at depth 5,000 feet, having a width of 10,000 feet and a relief of 500 feet? The 500 feet of relief becomes 1 thickness unit, the 5,000 feet of depth 10 thickness units, and the half width of 5,000 feet means a slope of $500/5{,}000 \times 0.1$, making the slope angle in the chart almost 6°. Assuming that the overlying sediments have negligible magnetization and the core has a magnetization of 500×10^{-6} (assumed on the chart), the anomaly expected will be about 7 gammas. Since the magnitude of the anomaly is directly proportional to the magnetization, we may substitute the actual earth's field in place of Z_0, and any reasonable susceptibility contrast for the $1{,}000 \times 10^{-6}$ assumed on the chart, and get a value for the maximum anomaly perhaps better related to the particular locality.

ROBERT J. WATSON
The Carter Oil Company



MAXIMUM ΔZ_z ANOMALY
OF △ SHAPED
ELONGATED ANTICLINES

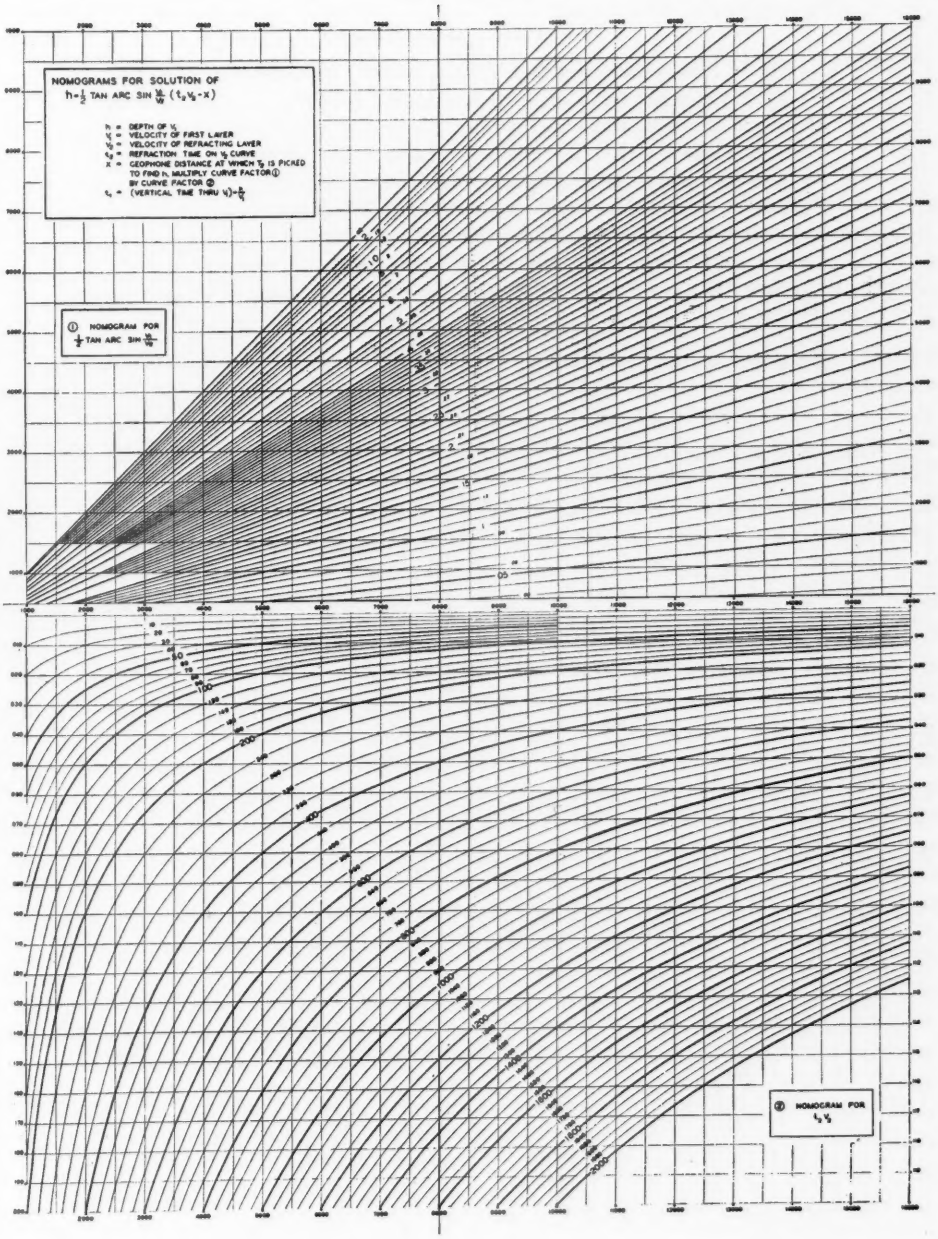
NOMOGRAM FOR SIMPLE TWO-LAYER SEISMIC REFRACTION PROBLEM

In seismic refraction work it is often convenient to use the simple formula $h=\frac{1}{2}$ arc sin $V_1/V_2(t_2V_2-x)$. This expresses the thickness h in terms of time and velocity of a bed of constant thickness and of velocity V_1 overlying a refracting bed of greater velocity V_2. Conditions of least travel time are satisfied when sin $\alpha=V_1/V_2$ by extension of Snell's law, where α, or arc sin V_1/V_2 is equivalent to the angle of emergence of refracted "rays." The value x is the horizontal receptor distance from the sound source. A simplification is afforded by picking the "intercept" (t_0) on the time distance graph, in which case $x=0$ and is eliminated from the equation. The nomogram provides solution of the problem by giving first the value of $\frac{1}{2}$ arc sin V_1/V_2 on the upper chart and the product V_2t_2 on the lower chart. The value x at which t is picked is then subtracted from this product (if the intercept is not used) and the values obtained from the two charts are multiplied to give the value of h.

The formula may be extended for additional parallel layers, and the nomogram may be used for the ratios and products involved in the extended formulae. Modifications to the formula can be made for the case of shots fired in shallow holes, or for the case of shots fired in deep holes at or near the contact of the V_1 and V_2 layers.

Example: A time distance graph shows V_1 (reciprocal of slope) to be 2,000 ft/sec and V_2 to be 5000 ft/sec. The intercept of the $1/V_2$ line is .032. By the charts $\frac{1}{2}$ tan arc sin V_1/V_2 is .218 and t_2V_2 is 160. Then the product $.218\times160$ equals h equals 35 ft. The low velocity time is 34.9/2,000 or .0175.

PAUL L. LYONS
Anchor Petroleum Company


NOMOGRAMS FOR SOLUTION OF
h = ½ TAN ARC SIN V1/V2 (t2V2 - x)
h = DEPTH OF V1
V1 = VELOCITY OF FIRST LAYER
V2 = VELOCITY OF REFRACTING LAYER
t2 = REFRACTION TIME ON V2 CURVE
x = GEOPHONE DISTANCE AT WHICH T2 IS PICKED TO FIND h, MULTIPLY CURVE FACTOR① BY CURVE FACTOR ②
t1 = (VERTICAL TIME THRU V1) = h/V1
① NOMOGRAM FOR ½ TAN ARC SIN V1/V2
② NOMOGRAM FOR t1V1

REVIEWS

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Interpretation of Aeromagnetic Maps, by V. Vacquier, N. C. Steenland, R. G. Henderson and I. Zietz, G.S.A. Memoir 47, New York, Nov. 1951, 151 pp., $2.25.

This memoir is a veritable mine of theoretical anomaly patterns for total intensity and "curvature." It should be considered practically indispensable for the interpreter of total intensity surveys

who tries to estimate the depths and shapes of bodies causing the anomalies on his maps unless he has had the time and energy to produce a similar set of patterns. The four authors are to be commended for the production and publication of this work.

The anomaly patterns are given for a series of theoretical bodies having the following properties:

1. Magnetization in the direction of the earth's field at various magnetic latitudes (0°, 20°, 30°, 45°, 60°, 75° and 90°).
2. Uniform susceptibility contrast with respect to the surrounding material.
3. Vertical sides extending infinitely downward (except for special cases).
4. Upper surface horizontal and one unit distance below plane of map.
5. Rectangular shape in plan. The dimensions, expressed in depth units, vary from $\frac{1}{2}\times 6$ to 8×8, thus including various degrees of rectangularity as well as the square shape.
6. The elongated bodies are presented with orientations, north-south, east-west, and northeast-southwest to show variation of pattern with strike, especially in the lower latitudes.

A numerical method of interpretation is described which makes use of certain critical distances measured on the field anomalies and referred to the theoretical anomaly patterns in total intensity and curvature. Areal shape and susceptibility contrast of the disturbing body are inferred. To facilitate the interpretation, tables and graphs of "depth indices" are given which allow these critical distances to be translated into depth to top and areal extent of the body. The indices cover the range of magnetic latitudes noted above, the three orientations, and the variation of areal extent with respect to depth.

The total intensity anomalies were computed by a method apparently devised by Vacquier. It is described in sufficient detail with the aid of tables to allow further computations to be completed by others. The method can be adapted either for the case of the body having infinite or finite depth extent, should one be interested in the anomalies of bodies having small vertical relief, such as the basement cores of structures commonly sought in oil prospecting.

The "curvature" or "second vertical derivative" anomalies were computed by a method devised by Henderson and Zietz. This was published in *Geophysics*, Vol. 14, p. 508.

The memoir was a co-operative undertaking between the Department of Geology of Columbia University and the Geophysics Branch of the U. S. Geological Survey. Credit for instigating the work is due Vacquier who also contributes an excellent discussion of the general principles of the magnetic method, the geological information one may expect to infer from a magnetic survey, and the simplifying assumptions which were necessary for the computation and construction of the anomaly patterns. He concludes Chapter II as follows: "One of the objects of this memoir is to provide a uniform method of interpretation for the organizations now engaged in magnetic prospecting so as to pool the practical experience that is essential to the successful application of geophysics."

In Chapter III Steenland considers the actual application of the method and gives the results obtained from six aeromagnetic surveys which were flown over a variety of structural conditions. In three of these areas, Bagdad, Arizona, northeastern Umnak Island, and northern Adak Island, the masses of magnetization contrast causing the anomalies lie exposed at the surface. The depth to top is thus the height of the plane and a check on the accuracy of the method is available. The depths determined from the critical distances measured on the total intensity and curvature maps are in fair agreement with the height of the plane. For the Bagdad area, the plane flew at 1,000 ft above the surface, and the height computed from the magnetic anomalies varied from 920 to 1,200 ft. For the northeastern Umnak Island area, the flight level was 6,500 ft above the surface and the computed heights varied from 5,100 to 6,800 ft. For the northern Adak Island area, the flight level was 5,000 ft and the computed heights varied from 4,500 to 6,700 ft. Not all the anomalies on the maps were considered worthy of depth estimates. Grading of anomalies from their shape and degree of isolation can be done during the interpretation so that all the depths determined will not have the same weight. It would appear that in general only the order of magnitude of depth should be expected but for particular areas and particular anomalies better results are possible.

ROBERT J. WATSON

Introduction to Geophysical Prospecting, by Milton B. Dobrin, McGraw-Hill Book Company, New York, 1952, 435 pp., $7.00.

Dr. Dobrin explains in the preface that his *Introduction to Geophysical Prospecting* was written to meet a specific need for a textbook suited to the capabilities of students of Geology and Engineering whose mathematical background does not include calculus and whose training in physics has been on an elementary level. The book originated in lecture notes prepared for a course which the author taught for two years at Columbia University.

The book can be recommended for its intended purpose and is also recommended to geologists or executives whose work brings them into contact with geophysical work. It will probably be of little value to professional geophysicists although it may be profitably read by newcomers to the field.

The book considers all standard geophysical methods and their application to exploration for both petroleum and mineral deposits. It also covers the use of radioactivity measurements in the now popular search for uranium ore. Electrical and radioactivity well-logging methods are briefly treated in one short chapter while another chapter is devoted to an interesting discussion of the modern radio position-locating methods often used in making geophysical surveys. One of the most valuable chapters in the book is devoted to case histories of actual geophysical surveys made for both petroleum and ore bodies. While all the case histories cited have previously been published; their inclusion in the text, together with a sensible commentary, is considered to be of considerable value for teaching purposes and should help the reader evaluate both the possibilities and limitations of the various methods applied to specific problems.

In introducing each of the various prospecting techniques, the author takes some pains to indicate that none of them sprang full-blown to meet a need but each had a long and honorable background of scientific knowledge resulting from years of academic research. For example, the subject of seismic prospecting is introduced by an elementary discussion of seismology. The discussion of each method includes the underlying physical principles, instruments, field techniques, reduction of field data, and finally, interpretation. In general, the author is at his best when discussing underlying physical principles while his treatment of field techniques and the interpretation of data is less apt.

Six chapters of some 90 pages are devoted to gravity prospecting. On the whole this section is well and interestingly written. The important facts about the gravitational field of the earth, as well as the various theories of isostasy, are clearly presented. The description of instruments used in gravity prospecting is properly concerned primarily with gravity meters currently being used, including the recently developed Worden meter. The torsion balance and pendulum are but briefly mentioned. The field procedures used in making gravity surveys, and the reduction of data, are adequately treated. However, the discussion of interpretation is purely academic and not particularly enlightening.

The section of 74 pages devoted to magnetic prospecting is also well done. The treatment of the earth's magnetic field and its variations is interesting and sufficient. The Schmidt magnetic balance is clearly described in the text and by drawings. Interpretation of magnetic maps, admittedly a difficult subject, is only cursorily treated. An entire chapter is devoted to a description of the airborne magnetometer and its use, the chapter being well illustrated with pictures of the equipment and maps made by aerial magnetic surveys.

Refraction and reflection seismic methods are discussed in a section of 109 pages. The importance of the seismic reflection method is not sufficiently emphasized and the reviewer must take exception to the author's statement that reflection surveys ordinarily are not undertaken until other "cheaper" methods have been used to isolate anomalous areas for study. This section was disappointing to this reviewer. The author again is at home in his introduction dealing with seismology and in his account of the elementary theory of elastic waves, but fairs less well in discussing the practice of the methods. His description of instruments employed is well illustrated with pictures of modern equipment but the discussion of what they do and how they work is inadequate. The refraction method is ade-

quately treated, perhaps overemphasized as compared with the much more useful reflection method. However, the important technique of using arrival times of refracted waves other than the first arrival is mentioned only in passing. The section on reflection shooting is not too well organized and too much emphasis is given to unimportant details. Several pages and figures are devoted to descriptions of various arrangements of shot points and detectors which might better have been devoted to a more complete discussion of the geometry of reflection wave paths.

The single chapter on electrical methods discusses resistivity measurements briefly but does little more than mention other techniques. In view of the unimportance of electrical methods in prospecting for oil, possibly this treatment is sufficient. However, since inductive methods using alternating current are of very considerable importance in the search for shallow ore deposits, these methods might well have been more fully discussed.

The chapter on well-logging, although mentioning all methods ordinarily used, merely gives the reader a nodding acquaintance with the subject. The chapter on prospecting for radioactive minerals contains a brief and very readable elementary account of radioactivity and describes the use of gamma ray detectors in searching for uranium bearing minerals. The advantages of using scintillation counters in such prospecting are properly emphasized.

Throughout the volume, references are given to short bibliographies at the end of each chapter. The author has deliberately confined his references to easily available sources and to those treating their subjects on a rather elementary level. The majority of references are to recent literature, a very large number in *Geophysics*.

Dr. Dobrin undertook a difficult task in writing a text with the limitations he set, and has done it very well. His book is a welcome addition to the literature of geophysical prospecting. His publisher is also to be commended for the excellence of the format and the high quality of the numerous plates and figures. These matters are particularly important in a volume intended for use as a text.

W. T. Born
Geophysical Research Corporation

Petroleum Productive Capacity, by Committee on Oil and Gas Availability, L. F. McCollum, Chairman, National Petroleum Council, Washington, D.C., 1952, 102 pp., 40¢ (paper bound), $1.40 (cloth bound).

Petroleum Productive Capacity is a comprehensive report prepared by the National Petroleum Council, at the request of the Department of the Interior, Oil and Gas Division, on the present and probable future petroleum productive capacity and availability to the United States. It represents the results of a year's investigation by outstanding men in the industry; men with experience in all phases; exploration, development, refining, distribution, finance, economics, and research. The report is less than 100 pages long and is simply and concisely presented. It should be in the library of every S.E.G. and A.A.P.G. member.

A "review" of this report, in the usual sense, is out of order, but a few quotations from the text should suffice to impress the exploration geologist and geophysicist with its vital importance.

The major finding of our studies can be summarized briefly:

"Available supplies of oil and gas in the United States and the world are greater than ever before and are still increasing rapidly. Granted continuation of reasonable economic incentives and adequate supplies of materials, crude oil and gas may be counted upon to be available in abundance for the foreseeable future."

Referring to symposia conducted by the American Association of Petroleum Geologists in 1941 and again in 1951, the following is quoted:

"Some measure of the potentialities of the prospective petroleum provinces is indicated by the following:

"1. Of the 34 provinces considered to have possibilities in 1941, 20 have already proved to have production during the past ten years.

"2. In 43 of the 60 provinces listed in the 1951 symposium there are positive evidences of the existence of oil and gas, such as seepages, good showings in the wells drilled to date, or some actual production.

"3. About 15 percent of the area in the 60 provinces listed in the latest symposium is already under lease."

"Future availability of oil is frequently approached on the assumption that each new field reduces the possibilities of further discovery. A discovery may mean one less field to be found, but it may also mean that (1) remaining fields will be found more rapidly or (2) that it will lead to discovery of fields that might not be found otherwise. The discovery of a new producing field provides additional information as to formations and structures in which more oil may be found. The discovery of production in reef formations in Scurry County, ... The discovery of the Leduc field in Alberta Canada, ... The recent discoveries in the Williston Basin in North Dakota and Montana . . . . These examples illustrate the manner in which new discoveries add to the knowledge by which the petroleum industry finds additional fields. Discoveries of new fields frequently improve, rather than decrease the possibilities of finding more oil."

"The technology for locating oil has improved dramatically through the years. The widespread use of geology dates from about 1915 and is still increasing. The application of geology to surface evidence and subsurface conditions has been supplemented within the past quarter century by geophysical methods. Refinements in geophysical methods, plus the accumulation of additional knowledge through drilling, result in the location of many prospects and fields which could not have been found by earlier techniques. Aerial reconnaissance and the use of helicopters hasten the search for oil in areas previously inaccessible. Various methods of testing formations have been devised and improved to locate productive horizons. Improvements in all phases of exploration are constantly being made, with the result that new fields are being located at record rates."

"The reasons why the older producing provinces remain prospective are as follows: (1) improvements in exploration reveal new prospects not evident by earlier methods; (2) the ability to drill deeper opens up prospects below the shallow producing fields; and (3) the accumulation of information through exploration and drilling suggests possibilities of production elsewhere in the same formations that have proved productive in the past."

"The prospects for finding substantial oil in areas which have had little exploration in the past may be considered good for the following reasons: (1) the geologic conditions of these prospective areas are generally similar to those of areas already producing; (2) there are already indications of the existence of oil and gas in some of the prospective areas, although very little exploration has been done; and (3) large sums of money are being risked by oil companies on exploration and leasing in prospective areas."

"The size of the prospective oil area is so large that exploration will have to be carried on for scores of years to test the possibilities thoroughly by present methods and at present rates. There is no lack of places in which the search for oil may be successful. As our technology improves steadily the search is being extended successfully to additional areas not previously considered prospective. A major new device for finding oil may accelerate the discovery in the prospective area, but it is not essential to future supplies. The progress made by the industry in the discovery of oil has been largely in the improvement of processes known for a long time."

"Greater knowledge, improved technology, and increased exploratory work can continue to operate for a long time to come in a vast prospective area that gives promise of large supplies of oil for the foreseeable future."

Under "Exhibit A—Possible Future Petroleum Provinces," there is a brief summary of possible future oil provinces listed by the American Association of Petroleum Geologists. It would be well for all of us in the exploration field to familiarize ourselves again with these provinces.

RAY A. STEHR

Dana's Manual of Mineralogy, 16th Ed., by C. S. Hurlbut, Jr., John Wiley & Sons, New York, $6.00.

It may be a surprise to many that another revision of this popular handbook of mineralogy seemed necessary in less than a dozen years. More than any other factor an increasing rate in improvement in mineralogical methods and underlying concepts has been responsible for this latest revision. Aware of the need of assisting geophysicists, geologists, and engineers, as well as students, in the understanding of unfamiliar techniques, Professor Hurlbut has made additions of explanatory nature which present a simplified résumé of the methods and nomenclature of modern mineralogy and crystallography.

A new first chapter orients the reader by pointing out the scope and purposes of mineralogy. A brief history of mineralogy is followed by an introductory discussion of the nature of minerals, touching on crystallography, and physical, chemical, descriptive, and determinative mineralogy. Inasmuch as these topics are subsequent chapter titles, the reader is prepared by outline for the principal sections that follow. This introductory chapter lends meaning to both the *Manual* and to the science of mineralogy by discussing procedures of application. Actual instances are mentioned where mineralogical determinations, correct and incorrect, were decisive factors.

Partial revision of the chapter "Crystallography" brings this section abreast of modern usage by simplifying nomenclature within the orthorhombic, monoclinic, and triclinic systems. Unpopular prefixes: brachy-, macro-, clino-, and ortho- have been dropped from the text to be relegated to subordinate mention in the footnotes. When the trend is toward ever-increasing complexity, a return to simple English is welcome. As I. C. Russell aptly expressed it. "Geologists should use their mother tongue whenever it can be made to serve." All crystal forms in the triclinic system are now considered pinacoids, distinguishing between first-, second-, and third-orders. To express crystal-class symmetry, the Hermann-Mauguin symbols have been introduced.

A new section, "Crystal Chemistry," recognizes and fulfills a need in the chapter "Chemical Mineralogy." The dominance of the anion or anionic groups is recognized, but the discussion goes further to consider mineral properties which seem to deviate from those expected on basis of chemical composition alone. Understanding of the modern conception of the solid state is greatly facilitated by discussions of atomic arrangement and packing, and the types of chemical bonds.

Anyone expecting to find a more comprehensive list of minerals will be disappointed to learn that descriptive details, with minor exceptions, remain essentially unchanged. This revision has made no effort to extend its coverage beyond the approximately 200 mineral species of the Fifteenth Edition. Skutterudite has replaced discredited smaltite-chloanthite, collophanite has been dropped, and carnotite and lawsonite added. In keeping with the new section on crystal chemistry, helpful diagrams, illustrating the six three-dimensional networks of the Bragg and Bragg silicate classification, have been added together with valuable discussions of the six linkage patterns of the SiO_4 tetrahedra. Elsewhere the Sixteenth Edition has been only slightly changed.

Frequent use of such compound terms as "crystal chemistry," "chemical mineralogy," and "physical mineralogy" indicates that efforts in related physical sciences have been successfully combined within the field of mineralogy. Many workers who are themselves largely responsible for technical advances which have prompted this Sixteenth Edition have found themselves working in twilight zones between major sciences. The new *Dana's Manual of Mineralogy* offers them ready assistance with its concise descriptions and determinative tables for the most commonly encountered mineral species. This latest edition once more assures the continuing service of the *Manual*, a century-long service made possible through successive revision.

C. MEADE PATTERSON
Gulf Research & Development Company

Introduction to Geology, New Third Edition, by E. B. Branson, W. A. Tarr, Carl C. Branson, and W. D. Keller, McGraw-Hill Book Company, Inc., New York, 492 pp., $5.50.

As the title to this excellent textbook indicates, this third edition was prepared for the thinking and enjoyment of those students beginning a course in geology. It is not intended for the graduate student of geology, nor does it contain any information or reference to geophysical prospecting, oil production, or engineering. However, for the average geophysicist with little or no geological schooling or training it should furnish a sound basis on geological thinking and the origin and development of the present-day earth. It contains a minimum of technical phraseology, tables, charts, and wordy definitions.

The text is divided into two parts: Physical Geology and Historical Geology. The first part treats with the organization of matter, igneous rocks, physical agents constantly wearing away, changing

and rebuilding the earth with their resultant products, structures of rocks, and the violent forces of diastrophism and earthquakes.

The second part treats of "the succession of events through which the earth has passed." The entire geological sequence is simply and adequately presented from the origin and dawn of earth history through the succession of geologic eras from the Paleozoic to the Pleistocene or Glacial Epochs. Paragraphs on the Economic Products of each era or epoch are the only "commercials" in the text.

To the neophyte, this is truly a splendid, entertaining *Introduction to Geology*.

RAY A. STEHR

Principles of Geochemistry, by Brian Mason, John Wiley & Sons, New York, 1952, $5.00.

This book is a welcome addition to the limited literature on geochemistry. Dr. Mason presents a well-written survey of the basic ideas of the chemical processes and principles in the earth's crust. The historical summaries of geochemical thought are concise and unique. A particularly valuable property of the book is the carefully selected annotated bibliography at the end of each chapter. These references will lead any interested non-geochemist immediately to the best work in the field on a specific subject.

In contrast to the more encyclopedic work by Rankama and Sahama (Geochemistry, Chicago, 1949) which gives detailed information on each of the ninety-two elements, Mason's book deals largely with principles in a concise manner, thus complementing the earlier work. *Principles of Geochemistry* contains a much more up-to-date synopsis of modern cosmochemical theory than the earlier volume by Rankama and Sahama, but this may only reflect the very rapid development in this field.

The reviewer wishes that certain unnecessary technical jargon which is so characteristic of geological literature had been omitted. Thus we are introduced to the apparently useless quantities, the "clarke" and "clarke of concentration" (suggested by Fersmann) without any critical comment. Also, we are still hampered with such terms as neso-, soro-, ino-, phyllo- and tektosilicates. The concentration of such terms is quite small, however, and in this respect, *Principles of Geochemistry* is greatly superior to the Rankama and Sahama volume. This criticism of a few terms is a very minor matter and in no way is meant to reflect on the excellence of the book as a whole.

Principles of Geochemistry is heartily recommended to all scientists interested in the chemical processes of the earth's crust. Although it is written as a text for first year graduate students, it is a valuable summary of geochemical concepts even for workers in the field of geochemistry. The makeup and binding are up to Wiley standards and the price is reasonable.

J. LAURENCE KULP
Lamont Geological Observatory
(Columbia University)

Report of the Committee on the Measurement of Geologic Time 1950–1951, Division of Geology and Geography, National Research Council, Washington, D. C., 1952, 140 pp., $1.00.

It is always a pleasure to see the publication of another of the annual reports of the Committee on the Measurement of Geologic Time. The time dimension is so central to the field of earth science, yet the disciplines required for its determination so diverse, that it is only through such a medium as these reports that a geologist can follow developments with a reasonable expenditure of effort.

As in previous years, one of the most valuable sections of the report is the "Annotated Bibliography of Articles Related to the Measurement of Geologic Time," which has been found by the reviewer to be quite complete for the period covered. In addition to the bibliography, there is always an excellent summary of work in this field which provides the best starting point for any earth scientist who wishes to examine the contemporary research efforts in age determination. The remaining reports consist of selected supplementary reports ("exhibits") giving some detail on the most interesting work in the measurement of geologic time. This issue contains, "Abstracts of Papers Delivered at the Symposium on the Measurement of Geologic Time, American Geophysical Union, April 30

and May 2, 1951," "Extracts from the Preliminary Report of the Committee on the Measurement of Geologic Time in India 1947–1950," and "Natural Variation in Isotopic Ratios of the Chemical Elements (A Report to the Commission on Atomic Weights, International Union of Chemistry, Sept. 1951, by J. P. Marble)." The latter report is a concise but comprehensive survey of the literature on isotopic variations in nature. The reviewer is not aware of any other equally complete survey of recent vintage.

The Report is edited and largely written by Dr. J. P. Marble, Chairman of the Committee, and thus carries the authority of a careful scientist who has been active in this field for many years. The National Research Council continues a very worthwhile contribution to earth science by the publication of these reports.

J. Laurence Kulp
Lamont Geological Observatory
(Columbia University)

"The Theory and Design of Two Types of Portable Seismograph," by P. L. Willmore, *Monthly Notices of the Royal Astronomical Society, Geophysical Supplement*, Vol. 6, No. 2, Oct. 1950, pp. 129–137, 1 plate.

This is an excellent comprehensive article, compactly written in ten pages, describing the theory and basic design of two portable seismometers. In the first part of the paper, the limits of sensitivity of a direct coupled mechanical seismograph are discussed from the viewpoint of the power required to maintain angular oscillations of a critically damped suspended mirror through an angle somewhat in excess of the width of the diffraction maximum. The power, derived from the motion of the ground, is related to the suspended mass of the seismometer and also to its natural frequency. The smallest practical size of the oscillating mirror is taken as 0.2 mm in thickness and 3 square mm in area. The author then finds, assuming an efficiency of 25 percent in coupling the power to the mirror, that approximately $M_s A^2$ is 1.2×10^{-12}, where M_s is the suspended mass of the seismograph and A is the amplitude of the ground motion. Thus, to detect ground motion of the order of 10^{-7} cm, the suspended mass of a seismograph must weigh about 120 grams. This value would have to be increased by some factor to allow for friction; in one of the two instruments built the moving mass was 1.4 kilograms.

In the remainder of the paper, two types of portable instruments are discussed in which the optical system was replaced by electrical coupling to a recording galvanometer remotely without the use of electronic amplifiers. In the first type, a short-period moving coil relative to a fixed permanent magnet, was used; in the second type, a longer-period moving magnet relative to a fixed coil was used. Optimum natural periods of each type are discussed. Actual construction, operation procedure, and results are described. Sensitivity sufficient to resolve microceisms was achieved and with the first type of seismometer tremors from rock-bursts at distances up to 300 miles were recorded.

Note that formula (7) given as:

$$M_s A^2 \cong (113)\ 8\lambda^2 \rho abc$$

should read

$$M_s A^2 \cong (1/3)\lambda^2 \rho abc$$

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"Ueber das Spektrum Seismischer Wellen die Durch Sprengungen Erzeugt Werden," by H. Menzel, *Annali di Geofisica*, Vol. 4, 1951, pp. 301–322.

This article is presented as a general introduction to the question of how the spectral distribution of energy from an explosive source in the ground is determined. There is some indication that this work is to be followed by a more detailed study of several points treated very briefly in the present

article. Most of the individual processes which can alter the seismic spectrum have been treated in greater detail elsewhere although the author has referred to only two such papers. However, the inclusion in a single paper of a discussion of many such effects serves a worthwhile purpose. While the author has made many idealizing assumptions in the problems treated, he has formulated the mathematical problems in sufficiently general terms to permit attempted solutions for less idealized cases. His main attempt is to indicate the processes that would tend to concentrate seismic energy in the frequency region below 100 cps. The presented treatment is limited to that class of processes which can generally be described as interference effects. No attempt is made to include non-elastic effects such as frictional forces or non-linear displacements.

The first problem discussed is the simple geometrical optics case of interference between the energy source and its reflection at the free surface of the ground. The argument here rests upon the enhancement of the spectrum in that region of periods equal to the time difference between the original energy pulse and its reflection. The second problem, which is solved in a more complete fashion, is that of the damped oscillations of a sphere resulting from a pressure pulse on its interior surface. The sphere is defined as the region in the earth from which linear elastic effects start, following the non-linear effects nearer the shot. The form of the impulse assumed is $\phi(t)=Ate^{-\alpha t}$. The complete solution is given, but the details are discussed for two ranges of values for the constant α. These are expressed in terms of the relation between α and ϵ, where ϵ is the damping constant of the spherical oscillations. It is also shown that the logarithmic decrement of these spherical oscillations is 4.4 for a solid in which $\lambda=\mu$ (i.e., Poisson's ratio$=\frac{1}{4}$).

Finally, the author presents a detailed discussion of the mathematical procedures involved in calculating the change in the spectrum produced by a layer having elastic constants different from those of the media above and below it. The case of a layer much thinner than the wave length is solved in detail for the case of a plane wave at normal incidence. Also, he treats a layer at the surface whose thickness is approximately equal to the wave-length. Since both of these problems have been discussed previously without the restriction of normal incidence, there is little new information provided by the present discussion. However, there is considerable value in seeing these three problems treated in the same paper with the emphasis upon three mechanisms, other than attenuation, which tend to enhance the lower frequency region of a seismic spectrum.

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"The Interaction of Rayleigh and Stoneley Waves in the Ocean Bottom," by M. A. Biot, *Bulletin of the Seismological Society of America*, University of California Press, Berkeley, California, Vol. 42, No. 1, Jan., 1952, pp. 81–95.

This is a short and lucid analysis of the problem of surface wave propagation in a medium consisting of a liquid stratum (sound velocity c) overlying a semi-infinite elastic solid (shear velocity V_s). Biot shows that undamped propagation can occur when the phase velocity and frequency of the disturbance in the solid and in the liquid are so chosen that the impedances (ratio of normal stress to vertical particle displacement) at the interface are matched. This is the condition expressed by the period equation which is usually obtained by taking a particular solution of the wave equation and expressing the fact that it must satisfy the boundary conditions.

Particular emphasis is given to the study of the Stoneley wave which corresponds to the branch of the fundamental mode dispersion curve for which the phase velocity V is less than c. It is shown that the phase velocity curve for this mode passes through the point $V=c$ in a perfectly continuous fashion and tends to a limiting value for infinitely short wave lengths. This limiting phase velocity can be appreciably smaller than c for small velocity contrast and small Poisson's ratio. This branch corresponds to displacements and pressures which decrease exponentially in both directions away from the boundary; in other words, to true Stoneley waves. Due to the finite thickness of the liquid layer they are somewhat dispersive.

The mechanism of propagation of these waves is illustrated by means of an idealized example: A Stoneley wave can be propagated along the interface of two semi-infinite media, one of which can only transmit shear waves and the other only compressional waves. This shows that, as the wave propagates, energy is continuously passed back and forth across the interface, being alternately in the form of potential energy of shear on one side and kinetic energy on the other. Finally it is suggested that at least part of the energy of the *T* phase of submarine earthquakes could be propagated in this manner. This question would be an interesting one to investigate. Since the velocity of Stoneley waves in this case would be extremely close to that of sound-in-water, velocity would not provide a reliable criterion for deciding whether the *T* phase was propagated mostly as a SOFAR or a Stoneley wave. Probably amplitude versus depth measurements would be best for settling this question.

IVAN TOLSTOY

"An Investigation of the Uppsala Microseisms," by Markus Båth, Uppsala, 1949, 168 pp.

"The Microseismic Importance of Cold Fronts in Scandinavia," by Markus Båth, *Arkiv For Geofysik*, Band 1, *nr* 12, 1950, pp. 267–358.

"The Distribution of Microseismic Energy with Special Reference to Scandinavia," by Markus Båth, *Arkiv For Geofysik*, Band 1, *nr* 13, 1950.

The three works of Båth listed above constitute one of the most complete studies of microseisms published to date. The empirical phase of the study is limited almost completely to the microseisms recorded at Uppsala although the theoretical derivations are capable of more general applications.

The first and most comprehensive of the three works is based on a thorough statistical study of amplitudes, periods, and earth particle motion of microseisms recorded from 1921–1938. Amplitude variations are shown to be periodic with three cycles of 1, 11, and 28 years. The annual variation is directly related to annual cyclonic activity, the 11 year cycle to meridional displacements of cyclone tracks in turn related to sun-spot activity, and the last is less definite possibly because of the long period of the cycle.

Microseism groups are considered to be a beat phenomenon originating from interference of waves traveling different distances from their sources with periods calculated as increasing at the rate of 10^{-8} sec/cm. Calculations of microseism energy are made and are compared with the energy of sea waves and atmospheric turbulence available for microseism generation. The effective sea wave energy (in dimensionless units) is $37(10^{-7})$.

Directions of approach of microseisms have been determined following the methods of Lee and Bungers, and indicate that the Norwegian coast is the source, the nearest part of the coast being most effective. However, cyclonic storms over the North Atlantic would give similar azimuths. The weather data studied by Båth is given only for relatively close Atlantic waters (Iceland to Norway). Although Båth turns to a cyclonic source when no "coastal effect" can be found, he concludes that some "coastal effect" is the dominant cause of microseisms. Perhaps a consideration of weather beyond the range of his limited charts would remove ambiguity. This might also explain the "lag (up to 16 hours) between sea-waves and microseisms."

The study of ground motion supports the thesis that microseisms are Rayleigh waves.

The second work is a study of microseisms recorded at Uppsala which were associated with cold fronts from 1945–1949. A theoretical study is made for the rate of change of "effective coast length" for cyclonic and frontal passage. Atmospheric turbulence, sea-wave height, and microseisms are found to be greater for northerly than for southerly winds of the same velocity. Båth presupposes that the microseisms, which vary in the same direction as turbulence and sea wave height, are the products of the sea waves rather than the direct effects of turbulence.

This ambiguity does not exist for fronts off eastern North America where the most turbulent air is associated with offshore winds whereas the highest waves are onshore, generated by less turbulent

onshore winds. Frontal microseism storms are invariably associated with turbulent offshore winds of little sea-wave importance.

Although the 18 individual cases given do not clarify this ambiguity, they do support most other observations that microseisms decrease when fronts or cyclones are over land. Båth concludes that wind velocity (through effect on wave generation) and effective coast length are of about equal importance in microseism generation.

The third work is a study of the distribution of microseism energy for Scandinavia using records from Bergen and Uppsala for the years 1945–1949. Theoretical studies of energy distribution from a line source (the coast line) are made for four different assumptions. A study of 18 cases shows that periods are greater for *N-S* than *E-W* components at both stations, and greater at Uppsala than Bergen. When fronts pass the coast equidistant from both stations, the amplitudes are equal or slightly less at Bergen and have simultaneous variations. When fronts pass closer to Bergen, amplitudes are greater there and variations are 1 to 2 hours earlier than at Uppsala.

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"Further Study of the *T* Phase," by Maurice Ewing, Frank Press, and J. L. Worzel, *Bulletin of the Seismological Society of America*, University of California Press, Berkeley, California, Vol. 42, No. 1, Jan., 1952, pp. 37–52.

This paper deals with a new series of *T* phase records obtained from Pacific shocks and recorded at Hawaii (both on seismographs and on SOFAR hydrophones). These *T* phases have practically all water paths and the complications of an earlier study, estimated land path corrections, are thus avoided (Tolstoy and Ewing, 1950). Excluding a few records for which the epicenter location or timing is doubtful, the mean velocity obtained is 1.47 kilometers per second. Seismographs and hydrophone records are reproduced. This paper provides a decisive and final confirmation of the theory that the *T* phase is propagated either as pure compressional or coupled compressional waves through the ocean.

IVAN TOLSTOY

"Grundlagen der grossregionalen Gravimetermessungen für das Amt für Bodenforschung," (Basis of the regional gravity measurements for the Amt für Bodenforschung), by A. Schleusener, *Geologisches Jahrbuch* für 1943–1948, vol. 64, pp. 187–199.

This article describes problems of the German regional gravity survey in 1934–1945 for the Amt für Bodenforschung, the German "Geological Survey." The survey contained some 40,000 gravimeter observations, mostly made under the author's direction. Many of the problems discussed are of general interest and these will be summarized below.

The author states that regional gravity measurements must satisfy the following requirements:

1. High accuracy of the differences between the points observed, for use in geophysical prospecting.
2. Reliable absolute value determinations for regional geology, geodesy and theoretical geophysics.
3. A presentation of the data in a form convenient for further study and for more detailed measurements.

The first point, high accuracy, was assured by the choice of gravimeter. At first the gravimeters of Thyssen and Schleusener were used, later that of Graf.

The second point, reliable absolute value, was taken care of by observing a network of pendulum stations with distances from 50 to 150 km. The network was tied to the basic Potsdam pendulum station. Incidentally, a recalculation by A. Berroth of the original data of Kühnen and Furtwängler for this station showed that the previously accepted value was 13 mgal too high. The gravimeter

base stations were tied to the pendulum stations, then adjusted. The gravimeters were calibrated and checked against a suitable gravity difference determined by especially careful pendulum observations.

To fulfill the third point, the Bouguer anomaly was chosen for presentation. The purpose is to exhibit gravity contours representing the disturbing masses (i.e., density differences reflecting geological conditions) below some assumed datum plane. Here the problems center about the density for the station reductions. The first problem is selecting the proper densities. The classic method of using hand samples is well known to be inexact; however, the two newer methods, the "statistical" density determination and the Nettleton density profile, have not yet replaced it. The "statistical" method is a sorting of the observations to see if there is a correlation between the altitude and the gravity anomaly. It is rather a check of the density than a method of determining it. Similarly, in Central Europe the density profile appears to be of supplementary rather than of determinative value for the following reasons:

1. The course of a gravity profile from one valley to the next is often too irregular.
2. The hills often consist of the hard horizons. Thus the density found is not representative.
3. Often the assumption that the vertical gradient of gravity has its normal value is not justified.
4. To obtain a trustworthy density value two consistent determinations are needed so that usually three or more profiles are necessary.

The uncertainty of the density values led the author to two variations from the ordinary presentation of mapped Bouguer data: the use of density provinces and of discontinuities in the datum plane for the gravity station elevations. Within the boundaries of each density province a different surface density was used in reducing the gravity data.

In regard to the elevation datum plane, sea level was used for coastal areas. When the topography rose to some 100 meters, a new datum was selected. These higher datum planes were introduced because the densities are not usually known all the way down to sea level. The use of incorrect densities down to that level would produce misleading contours especially near the boundaries of density provinces. To keep the jumps in the contours between levels small and to make the gravity anomalies of the same order of magnitude as those on the map with sea level datum, the Bouguer correction was made for the material between the new datum plane and sea level, using the density 2.4 g/cm^3 in all cases. The choice of this value has no effect on the form of the contours as a variation in it merely changes all the gravity values on that datum by the same amount. The gravity contours show a discontinuity at each change of level. This discontinuity of course is of no geologic significance. One might think that it would be preferable to use a set of different density values or even a continuously changing density instead of the constant 2.4 g/cm^3 but such procedures would tend to remove the effect of the geologic structures which are of interest to the prospecting geophysicist.

Since the use of datum planes at different elevations introduces discontinuities in the gravity contours at the boundaries of changes, the author has also introduced a slanting datum plane conforming closely to the main valleys. It is true that such a plane causes a regional distortion of the contours but this is usually small. Below the slanting plane a constant density is again used. Above it, the Bouguer gravity values are computed either according to density provinces or with any more detailed density information available. V. Scheffers (Geländekorrekturen bei Gravimetermessungen im Gebirge, *Földtani Közlöni*, 77, p. 12, 1947) has even suggested the use of regular cylindrical or ellipsoidal datum surfaces but this involves obvious practical difficulties.

The author notes that the anomalous gravity value refers to the altitude of measurement, not the altitude of the projection on the datum. If the vertical gradient is computed from the gravity contours, the gravity values can be reduced to the reference datum. Opinions differ on the practical value of such a treatment.

In the bibliography on page 199 the volume number for the Hammer reference should be 4, not 6.

THOMAS A. ELKINS

"Das Newtonsche Raumpotential prismatischer Körper and seine Ableitungen bis zur dritten Ordnung," (The three-dimensional Newtonian potential of prismatic bodies and its derivatives through the third order), by Karl Mader, *Österreichische Zeitschrift für Vermessungswesen*, Sonderhelft 11, Wien, 1951, iii+74 pp.

This pamphlet contains formulas for the potential and all its derivatives through the third order with respect to the rectangular coordinates x, y, z, for the following bodies of constant density:

(1) Rectangular block of finite length in the positive and negative x directions, the cross section parallel to the yz plane being a rectangle with sides parallel to the y and z axes respectively.

(2) Same as (1) but now of infinite length in the positive and negative x directions.

(3) Triangular block of finite length in the positive and negative x directions, the cross section parallel to the yz plane being a triangle with two sides parallel to the y and z axes respectively. There are thus four different cases.

(4) Same as (3) but now of infinite length in the positive and negative x directions.

The formulas are closed mathematical expressions in terms of elementary functions and the derivations are given in detail for those who may wish to check the final results. It would have been helpful if some representative curves had been included. Doubtless the amount of computational work that would have been necessary caused the author to omit such examples. It is interesting to recall that some of these formulas are the very ones whose formidable nature incited Barton and other early workers in the field of gravity interpretation to the development of graphical and mechanical methods to avoid the overpowering amount of computation. Perhaps the newly developed high speed electronic calculating machines will restore these exact formulas to practical use.

Most geophysicists working with the gravity or magnetic methods have probably derived a few of these formulas for their own use. However, the reviewer doubts that anyone previously had done as complete a job as Mader, and workers in these fields will be grateful to him for publishing his results.

THOMAS A. ELKINS

"Electromagnetic Levitation of Solid and Molten Metals," by E. C. Okress, D. M. Wroughton, G. Comenetz, P. H. Brace and J. C. R. Kelly, *Journal of Applied Physics*, May, 1952, pp. 545–552.

This is a most unusual article. Faced with the problem of the contamination of melted metals by the crucible, the authors devise an ingenious solution by eliminating the crucible altogether. This is accomplished by floating the metal in an alternating electromagnetic field which also serves to melt the metal. The molten metal thus hangs freely in space as a pulsating form with a top-like shape, free from contact with any contaminating surfaces. In this suspended state additions may be made to the melt, it may be cooled and thereby solidified while suspended, or the melt may be drawn off while still molten. Design data are given for maintaining a stable levitation. It would appear that the method should have wide application in the preparation of very pure melts.

NORMAN RICKER

PUBLICATIONS RECEIVED

Listed below are publications received by the society since publication of the last issue. Periodicals indicated by the asterisk (*) have been forwarded to the Standing Committee on Reviews, and will be placed in the permanent depository of the society at the University of Tulsa Library. These publications are available for loan to members of the society on application to the business manager. Other publications are held for a short time at the business office. Disposition of books listed is by direction of the Standing Committee on Reviews.

Periodicals

American Journal of Science, Vol. 250, Nos. 6, 7 & 8 (June, July & Aug., 1952)
**Annales de Geophysique*, Vol. 8, No. 1 (1952)
**Annali di Geofisica*, Vol. 5, No. 1 (Gennaio, 1952)
**Boletin de la Asociacion Mexicana de Geologos Petroleos*, Vol. III, No. 7–10 and No. 11–12 (July–Oct. & Nov.–Dec., 1951)
**Bulletin of the Earthquake Research Institute, Tokyo*, Vol. 30, No. 1 (March, 1952)
**Bulletin of the Geographical Survey Institute*, Vol. 2, Nos. 2–3 & 4 (June & Oct., 1951)
**Bulletin of the Seismological Society of America*, Vol. 42, No. 2 (April, 1952)
**Deutsche Geodatische Kommission*, No. 1 (1951)
**Deutsche Hydrographische Zeitschrift*, Vol. 5, No. 1 (1952)
Economic Geology, Vol. 47, No. 3 (May, 1952)
Erdol und Kohle, Vol. 5, Nos. 5 & 6 (April, May & June, 1952)
**Geophysical Exploration* (S.E.G. of Japan), Vol. 4, No. 3 (1951); Vol. 5, No. 1 (1952)
**Gerlands Beitrage zur Geophysik*, Vol. 62, No. 3 (1952)
Journal of Applied Physics, Vol. 23, Nos. 4, 5 & 6 (April, May & June, 1952)
**Journal of Geophysical Research*, Vol. 57, No. 1 (March, 1952), No. 2 (June, 1952)
Journal of the Institute of Petroleum, Vol. 38, Nos. 339 & 340 (March & April, 1952)
**Nafta*, Vol. 8, Nos. 4 & 5 (April & May, 1952)
**Proceedings of the Cambridge Philosophical Society*, Vol. 48, No. 3 (July, 1952)
**Quarterly Journal of the Geological Society of London*, Vol. 107, Pt. 2, No. 426 (May 12, 1952)
Review of Scientific Instruments, Vol. 23, Nos. 4, 5 & 6 (April, May & June, 1952)
**Revista di Geofisica Applicata*, Vol. 12, No. 2 (1951)
**Revista do Clube de Engenharia*, Vol. 25, No. 186 (Feb., 1952)
**Rocznik*, Vol. 21, No. 1 (1951)
**Science*, Vol. 115, Nos. 2993–3002 (May 9–July 11, 1952); Vol. 116, Nos. 3003–3004 (July 18 & July 25, 1952)
**Science Reports of the Tohoku University*, Vol. 3, No. 3 (Dec., 1951)
**Scientific Monthly*, Vol. 74, No. 6 (June, 1952); Vol. 75, No. 1 (July, 1952)
**Sintesi Economica*, Vol. 4, No. 4–5 (April–May, 1952)
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**Vrania*, (Octubre–Diciembre, 1951)

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Tiratsoo, E. N., *Principles of Petroleum Geology*, McGraw-Hill (1952)
von Engeln, O. D., and Caster, Kenneth E., *Geology*, McGraw-Hill (1952)

LETTER TO THE EDITOR OF *GEOPHYSICS*

A NOTE ON DIPOLE RADIATION IN A CONDUCTING MEDIUM

JAMES R. WAIT*

ABSTRACT

The steady-state fields of both electric and magnetic dipole elements in a conducting medium are discussed numerically. The dependence of the fields on the dielectric constant is noted.

Considerable interest has been shown recently in the propagation of electromagnetic waves in a conducting medium. The experimental investigations are often carried out at frequencies such that the fields are observed at distances within a few effective wavelengths from the transmitting antenna.[1] The nature of the radiated fields of a short antenna in this range is not as complicated as is commonly supposed. Also the effect of displacement currents which are usually neglected can be included. This latter point is important since dielectric constants of large values[2] are not uncommon.

It then seems desirable to present curves which show the true nature of both electric and magnetic dipole radiation in a conducting medium of infinite extent. The conductivity, dielectric constant, and the magnetic permeability are given by σ, ϵ, and μ respectively in M.K.S. units. The fields vary with a time factor $e^{i\omega t}$. An electric dipole or current element Ids is situated at the origin of a spherical coordinate system (r, θ, ϕ) and is oriented in the polar direction as shown in a previous paper.[3] The steady-state field components are:

$$E_\theta = \frac{Ids \sin\theta \cdot B}{4\pi(\sigma + i\omega\epsilon)r^3}$$

$$E_r = \frac{Ids \cos\theta \cdot A.}{2\pi(\sigma + i\omega\epsilon)r^3}$$

$$H_\phi = \frac{Ids \sin\theta A.}{4\pi r^3}$$

where

$$A = (1 + \gamma r)e^{-\gamma r}$$

and

$$B = (1 + \gamma r + \gamma^2 r^2)e^{-\gamma r}$$

$$\gamma = [i\sigma\mu\omega - \epsilon\mu\omega^2]^{1/2}.$$

The corresponding fields of the magnetic dipole of strength IdA are given by[3]

$$H_\theta = \frac{IdA \sin\theta \cdot B}{4\pi r^3}$$

$$H_r = \frac{IdA \cos\theta \cdot A}{2\pi r^3}$$

$$E_\phi = -\frac{i\mu\omega IdA \sin\theta A}{4\pi^2}$$

where A and B are defined above.

In both the electric and magnetic dipole formulas the factors A and B are to be interpreted as corrections to the static fields for finite values of the wave parameter γr.

The magnitude of the functions A and B are plotted in Figure 1 against a parameter $(\sigma f)^{1/2} r$ where f is the operating frequency in Megacycles per second and σ is the conductivity in mhos per metre. Various curves are shown for typical values of the dielectric parameter Kf/σ where K is the

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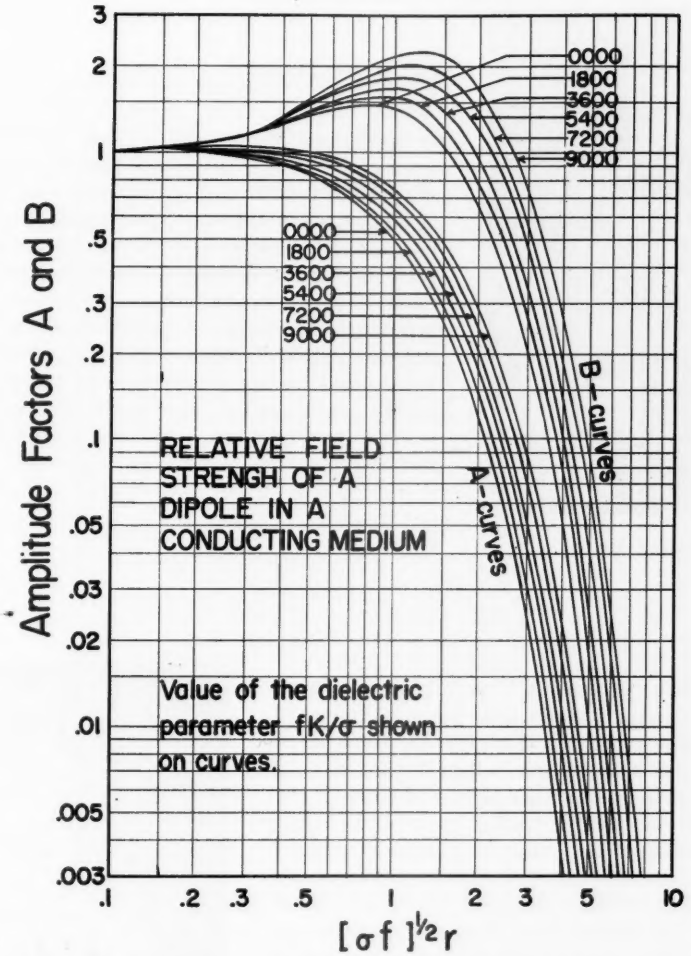

FIG. 1. Relative field strength curves of a dipole in a conducting medium.

dielectric constant of the medium relative to free space. The value of the magnetic permeability is taken to be that of free space.

It can be seen that for finite values of the dielectric parameter the attenuation is considerably less than would be obtained if displacement currents were neglected. For example, at a frequency of 0.1 Megacycles per second with a relative dielectric constant of 100 and a typical rock conductivity of 2×10^{-3} mhos per metre the parameter Kf/σ has a value of 5,000. It is then apparent that for distances greater than 100 metres the field strength is greater by a factor of three than the corresponding value when the relative dielectric constant is only 10.

The assistance of Mr. Lorne Campbell in preparing the curves is gratefully acknowledged.

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3. J. R. Wait, *Geophysics*, XVI, 2 (1951), 213–221.

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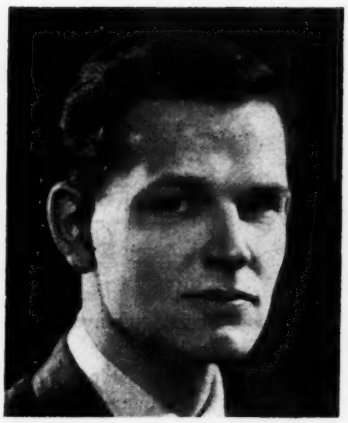

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PAUL FULLERTON

PAUL FULLERTON was born in Denver, Colorado, where he attended public school. In 1948 he received the B.S. degree in Applied Chemistry from California Institute of Technology.

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Mr. Glenn was employed by civil engineering consulting firms in Oklahoma and Texas prior to World War II. He served in the rank of Captain, U. S. Air Force, during the war, engaged in research in tropical meteorology and meteorological and oceanographic forecasting for Air Force and Navy construction and combat operations in the Pacific. Following the war he became Oceanographer at the USAF Weather Service in Washington, D. C. Since 1947 he has been a consultant in meteorology and oceanography. His company is A. H. Glenn and Associates, New Orleans, Louisiana.

Mr. Glenn is a Professional Member of the American Meteorological Society, and Fellow in the Royal Meteorological Society. He is a registered professional engineer in Louisiana and Texas, and holds membership in the ASCE, AIME, AAAS, American Society of Limnology and Oceanography, American Geophysical Union, and Svenska Geofysiska Foreningen.

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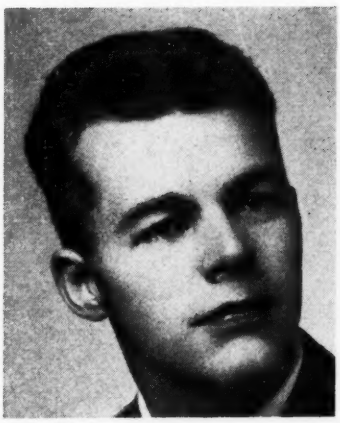
JOHN J. JAKOSKY, JR., received his degree in Petroleum Engineering from the University of Southern California in 1948. During the period from 1943 to 1946, he was in the U. S. Navy engaged in Radar and other high frequency developments. After graduation, he entered the employ of International Geophysics, Inc., and has been identified with Mid-Continent, Gulf Coast, California, and Canadian operations. His present position is Party Chief, with headquarters at Carlsbad, New Mexico.

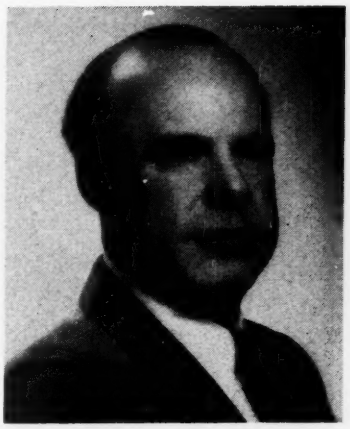
R. W. JAMES received the B.S. degree in meteorology and the M.S. degree in meteorology-oceanography from New York University. He has participated in the Beach Erosion Board Research Contracts on wave forecasting and refraction problems on the East Coast and in the Office of Naval Research Contracts on several reflection and refraction phenomena employing wave tank and wave analyzer. He presently holds the position of meteorologist with A. H. Glenn & Associates in New Orleans, La. Mr. James is the author of several papers on wave forecasting, refraction, and beach erosion. He is a member of the American Meteorological Society, American Geophysical Union, and Sigma Xi.



R. W. JAMES

C. D. McCLURE received the B.A. degree in Physics from the University of Wichita, Kansas, in 1935. From 1935 to 1937 he was a Graduate Assistant in the Physics Department of the University of Kansas from which he received his M.A. degree in 1937. He came to the Magnolia Petroleum Company in 1937 as a geophysical helper on a torsion-balance field crew. During ten years in the Geophysical Department of Magnolia Petroleum Company, he was successively: torsion balance operator, gravity-meter operator, gravity computer, and development engineer at the Geophysical Laboratory. He transferred to the exploration research division of the Field Research Laboratories of the Magnolia Petroleum Company in 1947. His work at the Field Research Laboratories has included electrical prospecting research, electrical field crew Party Chief, and geological research activities.

He is a member of the American Physical Society and the Dallas Geophysical Society.



C. D. McCLURE

FREDERICK ROMBERG

FREDERICK ROMBERG received his B.A. degree from the University of Texas in 1929. He spent the year 1929–30 in the geophysical department of the Humble Oil & Refining Company, and 1932–33 as a tutor in the Physics Department at Harvard. In 1933 he was employed by Geophysical Service, Inc. He was for some years chief of a seismograph field party, and later worked on the development and application of new interpreting methods, especially with respect to horizontal changes in seismic velocities. At present he is Southern Division Manager for Geophysical Service, Inc. at Houston, Texas. He is a member of the Seismological Society of America, Sigma Xi, and Society of Exploration Geophysicists.

WILLIAM SCHRIEVER

WILLIAM SCHRIEVER received his A.B. degree with a major in physics from Morningside College, Sioux City, in 1916. He was awarded a scholarship in physics at the State University of Iowa and received his M.S. degree in 1917. He enlisted in the Signal Corps in 1918 and served at what is now the Bell Laboratories and at Camp Alfred Vail in the development of interairplane radio telephone communication. He returned to his fellowship in physics at Iowa for a semester, and in the fall of 1919 became Assistant Professor Physics at the University of Oklahoma. During 1920–21 he continued his studies at Iowa and was awarded the Ph.D. degree. He returned to Oklahoma that fall, was promoted to Associate Professor in 1924 and to Professor in 1927. He has been chairman of the Department of Physics since 1942. He holds membership in the Society of Exploration Geophysicists, American Geophysical Union, American Association of Physics Teachers, Sigma Xi, Gamma Alpha, Sigma Pi Sigma, Sigma Gamma Epsilon; he is a fellow of the American Physical Society and of the American Association for the Advancement of Science.

EDWARD NELSON SKOMAL received a M.A. degree from the Rice Institute in June 1949 having majored in physics. Upon graduation he began work for the Field Research Laboratories of the Magnolia Petroleum Company, Dallas, Texas. In September 1951 he went to the National Bureau of Standards, Washington, D. C., where he is now located.

PAUL M. TUCKER received his B.S. degree in geology in 1935 from Michigan State College. He was employed by the Carter Oil Company from 1935 through 1944 in various capacities of seismic exploration. In 1945 he transferred to Standard Oil Company (N. J.) doing geophysical interpretation in Cuba and the Dominican Republic. In 1946 he joined the Standard Oil Company of Cuba as geophysical interpreter. In 1947 he became chief interpreter for Tropical Oil Company, Bogota, Colombia and in 1948 was advanced to the position of assistant chief geologist. In 1949 he became chief geologist with Tropical retaining that position until 1951. At present he is on temporary assignment with Standard Oil Company (N. J.) in New York for International Petroleum Company, Ltd.

Mr. Tucker is a member of the Society of Exploration Geophysicists.

PAUL M. TUCKER

In addition, references are cited to earlier issues for biographies of: Joseph A. Sharpe, Vol. VII, No. 2 (April 1942); John C. Cook, Vol. XVII, No. 3 (July 1952); Darrell S. Hughes, Vol. XVI, No. 4 (October 1951); Fraser S. Grant, Vol. XVII, No. 2 (April 1952); W. Jacque Yost, Vol. XVII, No. 1 (January 1952); Theodor Krey, Vol. XVI, No. 3 (June 1951); Neal Clayton, Vol. XVI, No. 1 (January 1951); and J. J. Jakosky, Vol. XII, No. 3 (July 1947).

SOCIETY ROUND TABLE

COMMITTEES

Executive Committee, Year Ending in April, 1953

President: Curtis H. Johnson, General Petroleum Corporation, Los Angeles, California
Vice President: Roy L. Lay, The Texas Company, Houston, Texas
Secretary-Treasurer: Carl L. Bryan, Consultant, Shreveport, Louisiana
Editor: Paul L. Lyons, Anchor Petroleum Company, Tulsa, Oklahoma
Past President: Sigmund Hammer, Gulf Research and Development Company, Pittsburgh, Pa.

Standing Committee on Nominations

Chairman: Curtis H. Johnson, General Petroleum Corp., Los Angeles, California
Sigmund Hammer — George E. Wagoner

Standing Committee on Membership

Chairman: Francis F. Campbell, Amerada Petroleum Corp., Tulsa, Oklahoma

Standing Committee on Honors and Awards

Chairman: Sidon Harris ('53), Southern Geophysical Co., Fort Worth, Texas
Norman Ricker ('54) — L. L. Nettleton ('55) — Andrew Gilmour ('56)

Standing Committee on Publications

Chairman: Wm. T. Born, Geophysical Research Corp., Tulsa, Oklahoma

Richard A. Geyer — R. W. Gemmer
R. A. Peterson — Cecil H. Green

Standing Committee on Program and Arrangements

Chairman: Roy L. Lay, The Texas Company, Houston, Texas

T. R. Shugart
D. R. Dobyns
R. E. Rettger
J. D. Divelbiss
Sidon Harris
T. I. Harkins
Roy F. Bennett
V. E. Prestine
Harold C. Bemis
Fred Forward
W. L. Homan
John M. Crawford
Reese H. Tucker
R. G. Piety
C. M. Moore, Jr.
Richard Brewer
L. F. Fischer
E. V. McCollum
Ralph B. Ross
Frank Press
A. van Weelden
Weldon L. Crawford
E. H. Shannon
W. H. Fenwick
Craig Ferris
N. C. Steenland

Standing Committee on Education

Chairman: J. B. Macelwane, S.J., Saint Louis University, St. Louis, Missouri

D. C. Skeels — Beno Gutenberg — Perry Byerly
M. King Hubbert — C. A. Heiland — John C. Hollister

Standing Committee on Distinguished Lectures

Chairman: Milton B. Dobrin, Magnolia Petroleum Co., Dallas, Texas

Standing Committee on Radio Facilities

Chairman: R. D. Wyckoff, Gulf Research and Development Co., Pittsburgh, Pennsylvania

Vice-Chairman: W. M. Rust, Jr., Humble Oil and Refining Co., Houston, Texas

Bart W. Sorge	C. B. Bazzoni	Daniel Silverman
E. M. Shook	V. Robert Kerr	Richard Brewer

Standing Committee on Reviews

Chairman: Nelson C. Steenland, Gravity Meter Exploration Co., Houston, Texas

Kenneth L. Cook	Richard A. Geyfr	Norman Ricker
Thomas A. Elkins	Lynn G. Howell	Robert J. Watson
Eugene W. Frowe	Robert C. Kendall	Milton B. Dobrin

Standing Committee on Publicity

Chairman: Robert C. Dunlap, Jr., Geophysical Service Inc., Dallas, Texas

Edward G. Schempf	A. E. McKay	C. G. Dahm
Wm. P. Ogilvie	E. L. Ricketts	Dale E. Turner
Robert Dyk	Eugene W. Frowe	L. D. Dawson, Jr.
Stanley W. Wilcox	Van A. Petty, Jr.	Lewis Riley
	Philip C. Ingalls	

Standing Committee on Annual Review of Geophysical Activity

Chairman: E. A. Eckhardt, Gulf Research & Development Co., Pittsburgh, Pennsylvania

A. A. Brant	Herbert Hoover, Jr.	D. C. Skeels	H. C. Bickel

Special Committee on Constitution and Bylaws

Chairman: W. M. Rust, Jr., Humble Oil & Refining Co., Houston, Texas

Henry C. Cortes	Andrew Gilmour	J. J. Jakosky
Cecil H. Green	Sigmund Hammer	L. L. Nettleton

Special Committee on Geophysical Case Histories Volume II

to be appointed

Special Committee on Safety

Chairman: Bart W. Sorge, United Geophysical Co., Inc., Pasadena, California

John F. Imle	Frank Searcy	W. H. Newton
C. C. Mason		H. C. Bickel

Special Committee on the Microcarding Project

Chairman: Milton B. Dobrin, Magnolia Petroleum Company, Dallas, Texas

Carl L. Bryan — Richard A. Geyer

Directors of the American Geological Institute

L. L. Nettleton (Nov., 1952) — Andrew Gilmour (Nov., 1953)

Representative on Division of Geology and Geography National Research Council

L. L. Nettleton, Gravity Meter Exploration Co., Houston, Texas
(June, 1954)

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee has approved for publication the names of the following candidates for membership in the society. This publication does not constitute an election but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it to the president within thirty days. Names of the references appear in parentheses after the name of each candidate.

ACTIVE

David Fitz Barnes (Henry R. Joesting, G. E. Manger, Mary C. Rabbitt)
Jay George Beaver (James Dorris, Robert E. Bush, T. A. Kibby)
Arnold H. Bleyberg (William C. Lamb, Don Gilkison, W. Bernard Robinson)
Richard De Chicchis (Ashton Crain, J. R. Bradley, Jr., E. E. Reynolds)
Bart John Dillon (A. G. Starr, John Bolinger, H. G. Patrick)
Bobby James Eubank (Roy L. Lay, Otis B. Hocker, C. R. Wallace)
Gerald Garth Gilbert (P. J. Rudolph, R. W. Upshaw, S. Preston Weatherby)
Warren Reller Hammel (Frank Ittner, T. E. Dennis, C. E. Reel)
Leo A. Markley (C. S. Fleischmann, J. B. Meitzen, G. O. Morgan)
Ronald George Mason (Cecil H. Green, C. Hewitt Dix, J. M. Bruckshaw)
Emil Frank Pechacek (Otis B. Hocker, J. S. Welboan, Jr., T. L. Kunkel)
Robert W. Pettersen (Cecil H. Green, F. J. Agnich, K. E. Burg)
Charles Lafayette Robinson (R. S. Duty, Jr., Eugene Frowe, J. C. Pollard)
Albert Henri Roger (Leon Migaux, W. B. Sibley, Jacques LeBlanc)
Adolfo Cosme Romero (S. Worden, W. C. Merritt, Peter Jacobsen, Jr.)
Sudhindra Narayan Sengupta (By-Laws III-2)
William Edgar Shamblin (F. O. Mortlock, C. M. Wert, W. B. Lee)
Charles William Shannon (James F. Johnson, Mark Milstein, William M. Barret)
James Mervin Smith (Roy L. Lay, C. S. Johnson, Robert N. Harding)
William Edward Strain (K. G. McCann, David H. Weinstein, Roy Butler)
Russell Herbert Talty (Sam D. Rogers, J. B. Nichols, J. R. Cornett)
John Charles Utesch (V. W. Teufel, H. B. Peacock, Ed. Stulken)
Rayford Warwick Winters (G. M. Mace, Jr., C. E. Meyers, B. K. Johnson)

ASSOCIATE

William Roger Angus (Harris Cox, F. E. Ellsworth, F. H. Hale)
Richard Paul Barnes (A. W. Black, C. K. Shepherd, B. G. Swan)
William Edward Bassinger (R. F. Bennett, F. A. Smith, S. B. Stewart)
John Ernest Betz (G. D. Garland, G. R. Johnson, J. T. Wilson)
Devon James Bevington (James F. Johnson, V. A. Peterson, L. F. Lockard)
Eugene Scott Bills (Andrew Gilmour, K. M. Lawrence, A. I. Innes)
Donald Edward Boren (Vernon J. Hunzicker, Herbert M. Dawson, P. J. Rudolph)
Francis Evans Boss (J. K. Ziegler, P. I. Bediz, C. Twardowski)
William Bradley (R. D. Everett, V. W. Teufel, Loyal Wells)
Charles Pricie Bragg (Jackson Young, R. W. Carter, B. J. Sorrells)
John Louis Brock (J. C. Porter, G. W. Martin, W. N. Walker)
Robert O. Cash (Roy L. Lay, William T. Born, Sidon Harris)
Earl Clark (Sigmund Hammer, L. I. Brockway, S. G. Pearson)
James Perry Cochran (E. V. McCollum, Craig Ferris, R. C. Sweet)
James Daniel Coons, Jr. (J. E. Lee, Jr., J. C. Palmer, R. T. Smith)
Robert William Coupland (James K. Ziegler, P. I. Bediz, Chester B. Twardowski)
David Braxton Darden (R. F. Bennett, F. A. Smith, S. A. Stewart)
Milford Howard Dingman, Jr. (Dupree McGrady, V. E. Prestine, Booth B. Strange)

Max William Dix (Leo J. Peters, Sigmund Hammer, James Affleck)
Sam L. Evans (M. E. Trostle, J. V. McManus, Ted Fryer)
James Frederick Farley (Samuel T. Martner, Paul D. Balbin, Philip H. Garrison)
George Kernan Fegan (C. C. Zimmerman, H. W. McDonnold, Robert P. Kennedy)
Alan Percival Fryer (C. C. Zimmerman, H. W. McDonnold, P. C. Cook)
Lawrence Eugene Grace (H. M. Thralls, J. G. Jackson, A. Maxwell House)
Ronald Walter Haskett (E. J. P. van der Linden, A. A. Fitch, V. V. Graf)
John C. Healy (Sam D. Rogers, Kirby E. Etheridge, Richard H. Benish)
Norman Henry Hill (E. L. Fetzer, Ira C. Mayfield, J. K. Ziegler)
Leman Milton Holley (R. W. Gemmer, W. H. Courtier, J. C. Rollins)
Gilbert Thomas Holmes (Robert Dyk, Paul Walton, Gordon Cloepfil)
James Robert Hughes (Fred J. Agnich, Roy Fuller, Robert Dyk)
John Robert Jacobsen (H. Wayne Hoylman, J. J. Jakosky, Clyde H. Wilson)
Rollyn P. Jacobson (Leroy Scharon, Carl Tolman)
Joe Harry Jones (James F. Johnson, Kirby J. Warren, L. O. Seaman)
William Blish Joyner (L. Don Leet, Henry R. Joesting, Kenneth L. Cook)
George Raymond Kaschak (James F. Johnson, V. A. Peterson, L. F. Lockard)
Charles A. Kehoe (Opie Dimmick, Roland F. Beers, Edward P. Kennedy)
John Herman Kosarek (A. B. Hamil, C. E. Myers, S. M. Pena)
Robert Frank Kraye (M. S. Hathaway, C. H. Hightower, Julian C. Ashby)
Alton Lavoy Linehan (V. W. Teufel, R. D. Everett, H. B. Peacock)
Vincent Kazmierz Litwinowicz (Fred L. Travis, Jr., J. E. Spencer, R. L. Schmidt)
Monzell Reed Louke (C. C. Zimmerman, H. W. McDonnold, Wm. G. Allen)
Don Dean Matson (C. G. Dahm, R. M. Nugent, J. C. Eley)
William Lathan Minter (John W. Byers, Hubert L. Schiflett, R. C. Hilton)
Richard Baines Minton (J. R. Winnek, K. M. Lawrence, C. J. Harvey)
Henry W. Morgan (Owen Wm. Anderson, Robbie Gene Rutherford, Paul D. Balbin)
William Paul Mounce, Jr. (C. E. Myers, Gordon M. Mace, A. B. Hamil)
Thomas C. Nichols, Jr. (W. H. Courtier, R. E. Beck, R. P. Clark)
Harold Porter Pauly (H. M. Thralls, H. H. Andrews, A. J. Barthelmes)
Charles Richard Pelton (B. G. Swan, H. E. Prokesh, Geo. H. Summers)
Aubrey Wayne Pogue (Sidon Harris, R. H. Dana, H. B. Mayo)
Alvin Carl Reinhardt (Roy L. Lay, C. R. Wallace, R. N. Harding)
Cecil John Rhodes (Robert A. Boulware, J. H. Frasher, Hugh P. Downey)
John Francis Rielly (Cecil H. Green, Chalmer J. Roy, Ray H. Wright)
Chester Rutkowski (F. Goldstone, F. A. Van Melle, L. F. Uhrig)
Halbert Sawyer (R. F. Bennett, F. A. Smith, S. B. Stewart)
Billy George Smith (T. F. Southgate, F. F. Campbell, Andrew Gilmour)
Richard Snyder (H. C. Towles, J. F. Rollins, G. Fisher)
Frank Payler Sonnenberg (William C. Lamb, Don Gilkison, Paul Weirich)
Horace Clayton Spence, Jr. (Perry R. Love, Glenn M. McGuckin, A. P. Marsh)
James Frederick Spencer (Robert Dyk, Roy Fuller, A. H. Smith)
Howard Allen Sykes (Leo J. Peters, Sigmund Hammer, James Affleck)
Don Tocher (Perry Byerly, Karl Dyk, Louis B. Slichter)
Wayne L. Underwood (Klaas van der Weg, W. B. Brinnon, C. G. Dahm)
Ross Watkins Whipple (Roy L. Lay, C. R. Wallace, P. M. Thompson)
Charles Douglas Vernon Wilson (A. van Weelden, R. Stonely)
Wilbur James Wright (M. W. Harding, Don C. Short, Flint H. Agee)
Raymond James Yuzbick (Roy L. Lay, Otis B. Hocker, J. S. Welboan, Jr.)

TRANSFER TO ACTIVE

Wilburn Frank Albers (Ewin D. Gaby, Geo. Augustat, John J. Babb)

Robert Allen Boulware (Walter H. Amis, Everett L. Campbell, James H. Frasher)
Warren Leslie Davis (H. R. Prescott, B. G. Swan, Paul R. Warren)
Dean McGuire Denton, Jr. (Roy L. Lay, J. S. Welboan, Jr., T. L. Kunkel)
Roy Lee Fuller (F. J. Agnich, R. C. Dunlap, Jr., K. E. Burg)
Winston Leonard Irwin (Roy L. Lay, T. L. Kunkel, C. R. Wallace)
Henry Woodrow Kale (Roy L. Lay, C. R. Wallace, J. A. Treybig)
John Manford Kendall (Roy L. Lay, L. A. Scholl, Jr., A. A. Hunzicker)
Carl Kisslinger (J. B. Macelwane, S.J., V. J. Blum, S.J., Frank Goldstone)
Anthony Mark Knouse (Roy L. Lay, Otis B. Hocker, C. R. Wallace)
William Paul Nelson (G. A. Berg, Sidney Schafer, Edward A. Kriege, Jr.)

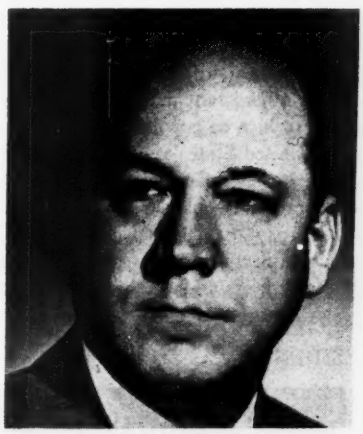
TRANSFER TO ASSOCIATE

Charles Derald Hachenberg (Frank T. Allen, Philip F. Cerveny, W. B. Agocs)
Jennings G. Smith (R. W. Gemmer, W. H. Courtier, J. C. Rollins)

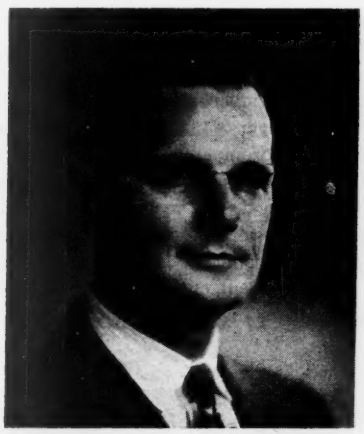
NOMINEES FOR 1953–54 EXECUTIVE COMMITTEE

The following brief biographical sketches are presented to acquaint members of the society with nominees appearing on the official ballot which will be mailed to all voting members at a later date.

FOR PRESIDENT



KENNETH E. BURG



ROY L. LAY

KENNETH E. BURG received his B.S. degree in Electrical Engineering from the University of Texas in 1926. Upon graduation he was employed by The Geophysical Research Corporation to do experimental geophysical work. Mr. Burg was computer and observer on one of the original experimental reflection crews and was in charge of several electrical prospecting crews prior to the time he was made Party Chief of a refraction crew in 1928.

In 1930 he joined the newly formed Geophysical Service Inc., and as Party Chief with that organization, he worked in the Gulf Coast, Mid-Continent, and Pacific Coast areas, and in Canada. He was placed in charge of the Southern Louisiana and Mississippi areas as District Supervisor in 1936 where he was instrumental in developing the techniques and equipment used in that area. Mr. Burg was one of the pioneers in reflection work in Canada, being in charge of work in the Alberta plains area in 1940 and 1941. He moved into Dallas in 1941 to become head of the Research Department in the Laboratories of Geophysical Service Inc.

Mr. Burg resigned in 1942 to join the Stanolind Oil and Gas Company as Seismograph Tech-

nician. In 1943 he was made head of the Seismograph Department, and in 1944 was promoted to Geophysical Supervisor and placed in charge of all the geophysical operations of the Stanolind Oil and Gas Company. He rejoined Geophysical Service Inc., in January 1947 as Consulting Geophysicist. In 1950 he was promoted to the position of Vice President Technical and placed in charge of equipment, field and office techniques, and research.

Mr. Burg is a member of the Society of Exploration Geophysicists, American Association of Petroleum Geologists, American Geophysical Union, Seismological Society of America, The Dallas Geophysical Society, Institute of Radio Engineers, and Tau Beta Pi Honorary fraternity. He has served on the Research Committee of the American Association of Petroleum Geologists, and has served the S.E.G. as a member of the regional program committee, as chairman of the Standing Committee on Membership, in the preparation of the *Cumulative Index* and as Secretary-Treasurer of the Society. He has also served as Vice-President of the Dallas Section and Chairman of the Program Committee for the first Dallas Regional Meeting.

Articles by Mr. Burg which have been published in *Geophysics* are "A Seismic Wave Guide Phenomenon" by Burg, Ewing, Press, and Stulken in the October 1951 issue and "Exploration Problems in the Williston Basin" in the July 1952 issue.

ROY L. LAY received his B.S. degree in Electrical Engineering from The Rice Institute in 1928. Upon graduation from Rice he was employed by the Geophysical Research Corporation as an observer and was later promoted to computer and party chief.

Mr. Lay was employed by The Texas Company as party chief in April, 1932, and during the next several years initiated this company's reflection work in Texas, Louisiana, California, and the Rocky Mountain area. He was promoted to field supervisor in 1937, and during the next year made a supervisory trip to Colombia and Venezuela, and he was in charge of the seismic, gravity, and magnetometer work in Egypt. In July, 1943, he was promoted to assistant chief of the geophysical division and in September, 1945, was advanced to the position of assistant manager. On April 1, 1950, he became manager of the geophysical division, the position which he now holds, having jurisdiction over The Texas Company's geophysical operations in the United States and Canada.

Mr. Lay is a member of the American Association of Petroleum Geologists, Houston Geological Society, and has been a member of the Society of Exploration Geophysicists since 1935. He was Second Vice President of the S.E.G. Houston Section in 1947–1948, President for the 1948–1949 term, and served on the executive committee of the Houston Section from 1949 to 1951. He is currently Vice President of the Society of Exploration Geophysicists and Chairman of Program and Arrangements for the forthcoming Annual Meeting.

FOR VICE PRESIDENT

KARL DYK

EUGENE W. FROWE

KARL DYK received his B.A. degree in Physics in 1929, and his Ph.D. in Seismology in 1934, both from the University of California. During the years following his graduation in 1929, and while studying for his doctorate, he worked with the U. S. Coast and Geodetic Survey, doing research in submarine acoustics. He continued with the Survey until 1935 when he joined Stanolind Oil and Gas Company as a computer on a seismograph party. A year later he was made party chief. He was transferred to Tulsa in 1939, serving as a geophysicist in Stanolind's main office. In 1945, he was made division geophysical supervisor of Stanolind's North Texas-New Mexico division, headquartered in Fort Worth. Two years later, in January 1947, he became supervisor of all Stanolind's geophysical operations and transferred back to the main office in Tulsa. A year later he was appointed chief geophysicist, the position he now holds, having jurisdiction over the technical aspects of Stanolind's geophysical operations in the United States and Canada.

Dr. Dyk is a member of the Geophysical Society of Tulsa, Tulsa Geological Society, American Association of Petroleum Geologists, Seismological Society of America, American Geophysical Union, Fellow of the Geological Society of America, Fellow of the Royal Astronomical Society, and a member of Sigma Xi. He has been a member of the Society of Exploration Geophysicists since 1938, and was General Chairman of the 5th Annual Midwestern meeting of the S.E.G. in Dallas, in May, 1951. Numerous articles by Dr. Dyk have been published in scientific journals, including *Geophysics*, as well as the *Proceedings of the National Academy of Sciences*, and the *Field Engineers Bulletin of the U. S. Coast and Geodetic Survey.*

EUGENE W. FROWE was born in Lawrence, Kansas, November 5, 1915. He received his B.A. degree in Physics from the University of Kansas in 1937, and after working a year toward a Master's degree, he accepted a position on a torsion balance crew with the Coastal Oil Finding Company. The crew was shortly converted to gravity meter operation, and Mr. Frowe worked in various capacities on this crew until early 1941 when he returned to the University of Kansas to complete his Master's degree. In July 1941 he went to work as a civilian for the Naval Ordnance Laboratory in Washington, D. C. Throughout the war he was engaged in mine countermeasures research, particularly the protection of ships against magnetic mines. In September 1945 he resigned from N.O.L. to go to work for the Robert H. Ray Co., with whom he is now associated as laboratory chief.

Mr. Frowe joined the Society of Exploration Geophysicists in 1945 and has been active in the Society ever since. A charter member of the Houston Section of the Society, he served his Section as secretary for the 1950–51 fiscal year and as first vice-president for the 1951–52 fiscal year. He served the national society as a member of the Standing Committee on Reviews for 1951–52. He is a member of the American Physical Society, the Institute of Aeronautical Sciences, the Texas Academy

FOR SECRETARY-TREASURER

W. B. ROBINSON

BART W. SORGE

of Sciences, the Houston Geological Society, the American Geophysical Union, Society of Exploration Geophysicists Houston Section, and the Society of Exploration Geophysicists.

W. BERNARD ROBINSON received the degree of B.S. in Electrical Engineering from the University of Nebraska in 1930. From 1930 to 1933 he was employed by the Westinghouse Electric & Manufacturing Co. Since that time he has done geophysical work for Gulf Research and Development Co., in the United States and in Venezuela. For the past ten years he worked at the Gulf Research and Development Co., Laboratories at Harmarville, Pennsylvania, as supervisor of interpretation for several seismograph parties. During that time he was active in the Pittsburgh Geological Society, serving at various times in the capacity of secretary, vice-president, and president. In February, 1952, he was transferred to Tulsa, Oklahoma, where he is geophysical supervisor for the Tulsa division of Gulf Research and Development Co.

BART W. SORGE was graduated from the University of California at Los Angeles with an A.B. degree in Physics in 1933. He did postgraduate work in Physics at U.C.L.A., receiving an M.A. degree in 1934. Upon graduation, his geophysical experience began with the Rieber Laboratories as a development engineer, and later geophysical observer, party manager, and party chief. Since 1938 he has been employed by the United Geophysical Company, serving as a development engineer, computer, and party chief until 1943. At that time he became geophysical supervisor of United's western operations, and since 1947 he has been a vice president of the company.

Mr. Sorge is a member of the Society of Exploration Geophysicists and the American Association of Petroleum Geologists. He has served the S.E.G. as chiarman of the Special Committee on Safety since 1951, as member of the Standing Committee on Radio Facilities since 1948, and as chairman of the Pacific Coast Regional Committee of Radio Facilities since 1948. As representative of the S.E.G. Special Committee on Safety, he is also a member of the Central Committee on Accident Prevention of the American Petroleum Institute. In connection with the recent 1952 annual meeting in Los Angeles, he served on the S.E.G. Arrangements Committee and the A.A.P.G. Technical Program Committee.

FOR EDITOR (TWO YEAR TERM)

MILTON B. DOBRIN

L. Y. FAUST

Milton B. Dobrin received his B.S. degree in Physics from the Massachusetts Institute of Technology in 1936, his M.S. in Physics from the University of Pittsburgh in 1941 and his Ph.D. in Geology from Columbia University in 1950. From 1937 to 1942 he worked on seismic interpretation for Gulf Research and Development Company at Pittsburgh and in the field. From 1942 to 1947 he was a physicist in the underwater acoustics division of the Naval Ordnance Laboratory. As a participant

in the Atomic bomb tests at Bikini Atoll during 1946, he was in charge of an underwater refraction survey to map the Atoll's structure.

From 1947 to 1949 he carried on graduate work in geology and geophysics at Columbia University, where, as Lecturer in Geology he taught two geophysics courses. He spent the summer of 1948 doing geophysical research at the Arctic Research Laboratory, Point Barrow, Alaska.

Since 1949, he has been employed by Magnolia Petroleum Company as a senior research technologist at its Field Research Laboratories in Dallas, where he has been carrying on research in seismic wave propagation.

Dr. Dobrin has written a number of papers for geological and geophysical journals as well as a textbook, *Introduction to Geophysical Prospecting*, which was published in January, 1952. He is a member of Sigma Xi, the American Geophysical Union, American Association for the Advancement of Science, The American Association of Petroleum Geologists, The Geological Society of America, Seismological Society of America, The Dallas Geological Society, The Dallas Geophysical Society (of which he is now First Vice-President), and the Society of Exploration Geophysicists. He has held the following committee assignments for the S.E.G.: Program and Arrangements (1945–48); Student Membership (1946–47); Case Histories Volume (1946–48); Reviews (1947– , Chairman, 1949–51); Distinguished Lectures, (1951– , Chairman, 1952–53); Microcarding of Geophysical Literature, (Chairman since 1951).

L. Y. FAUST was born in Clearville, Pennsylvania, in 1904. He received a B.S. degree in Physics from Franklin and Marshall College in 1925 and a Ph.D. in Physics from the University of Pennsylvania in 1930.

His geophysical experience began with the Sun Oil Company in 1926. Since 1930 he has been employed by the Geophysical Research Corporation and Amerada Petroleum Corporation, serving as a seismograph party chief until 1933 and as a geophysical supervisor since that time. His present duties are concerned with the study of special geophysical problems and seismic interpretation.

Dr. Faust is a member of the Society of Exploration Geophysicists and the American Geophysical Union. He is the author of "Seismic Velocity as a Function of Depth and Geologic Time," for which he received the Award for the best paper published in 1951 *Geophysics*.

ANNOUNCEMENTS

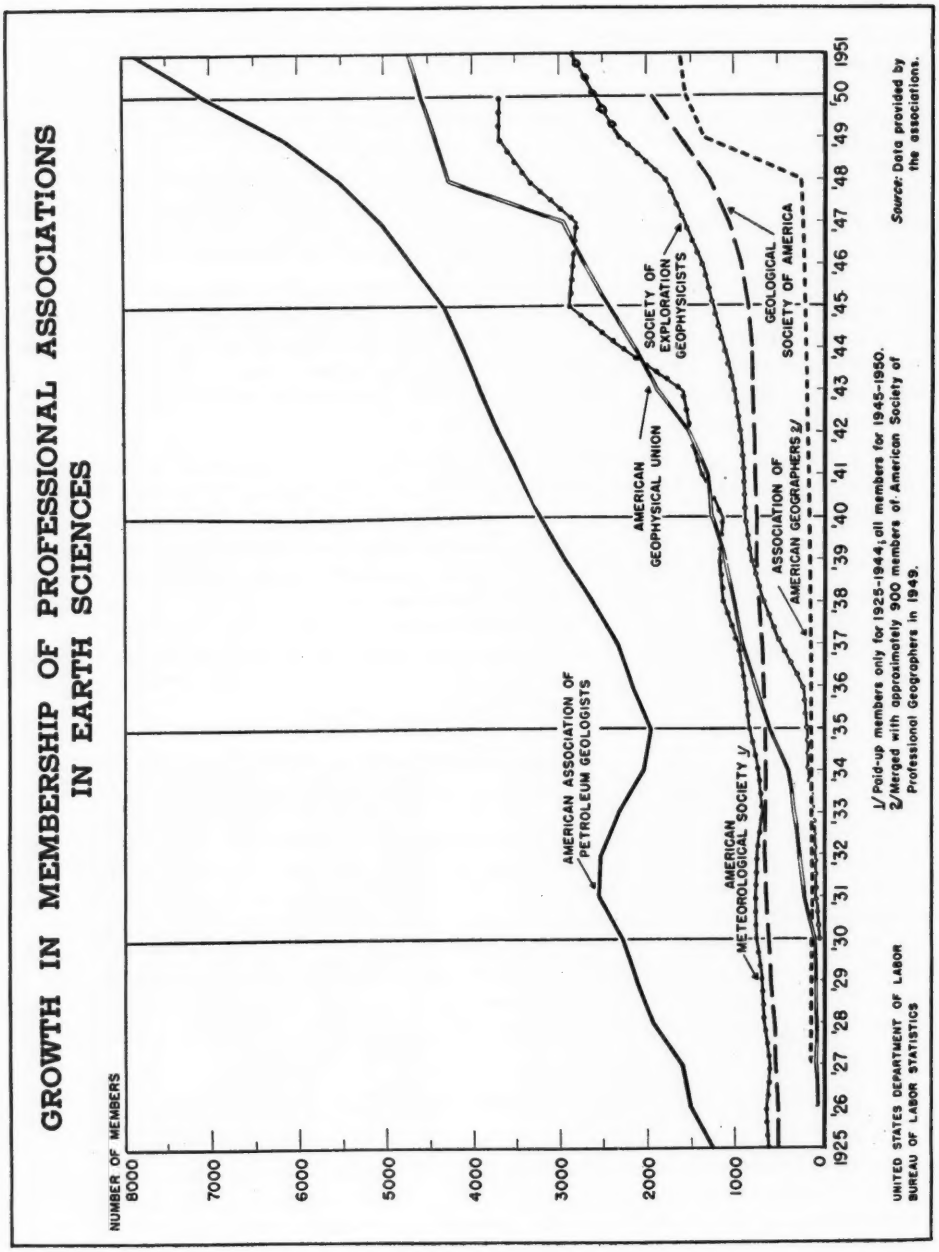
KIRKLINGTON HALL RESEARCH CENTRE

An article describing the establishment and development the Kirklington Hall Research Centre, near Nottingham, England, appeared in the July issue of the *Oil Forum*. The article, entitled "Back Door Oilfield Speeds British Research" is by P. Docksey, manager of the research centre. The laboratory is staffed by a nucleus of geophysicists, petroleum engineers and mud chemists, and is maintained by Anglo-Iranian Oil Co., Ltd., largest all-British oil company. The lab is located on the "pitching end" of the Eakring-Duke's Wood oilfield, a pool developed during World War II. Site is Kirklington Hall, a large manor on the edge of legendary Sherwood Forest. The modern research centre is used for testing instruments, tools, and machinery of its own design as well as those developed independently.

EMPLOYMENT OUTLOOK FOR EARTH SCIENTISTS

Demand for earth scientists is rising as a result of the defense program, according to the U. S. Department of Labor's Bureau of Labor Statistics. Geologists and geophysicists are needed to help provide more petroleum and minerals; meteorologists, to furnish additional weather data for military air force operations; geographers, to supply information on foreign countries important in defense planning; and oceanographers, to carry on research relating, for example, to submarine operations and amphibious landings.

These and other defense-connected and peacetime needs are described in the Bureau's new bulletin on "The Employment Outlook for Earth Scientists." The bulletin, prepared in cooperation with the Veterans Administration, is one of a series designed for use in vocational counseling of stu-


GROWTH IN MEMBERSHIP OF PROFESSIONAL ASSOCIATIONS IN EARTH SCIENCES
NUMBER OF MEMBERS
8000
7000
6000
5000
4000
3000
2000
1000
0
1925 '26 '27 '28 '29 '30 '31 '32 '33 '34 '35 '36 '37 '38 '39 '40 '41 '42 '43 '44 '45 '46 '47 '48 '49 '50 1951
AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
AMERICAN METEOROLOGICAL SOCIETY 1/
AMERICAN GEOPHYSICAL UNION
SOCIETY OF EXPLORATION GEOPHYSICISTS
ASSOCIATION OF AMERICAN GEOGRAPHERS 2/
GEOLOGICAL SOCIETY OF AMERICA
UNITED STATES DEPARTMENT OF LABOR
BUREAU OF LABOR STATISTICS
1/ Paid-up members only for 1925-1944; all members for 1945-1950.
2/ Merged with approximately 900 members of American Society of Professional Geographers in 1949.
Source: Data provided by the associations.

dents, veterans, and others interested in choosing a field of work. Later reports in the series will discuss the outlook in other fields of science. The present study was made in consultation with the professional societies of earth scientists. It includes information on the nature of the work done in the major earth science specialties, training requirements, places of employment, and earnings, in addition to a discussion of employment trends and outlook. The report (BLS Bulletin No. 1050) is available from the Superintendent of Documents, Washington 25, D. C. for 30 cents.

The earth scientists in greatest demand are those with extensive training and experience who are able to organize and direct either research projects or operating programs, particularly in the petroleum and mineral industries and in Government service. In certain highly specialized areas, such as research geophysics and meteorology, the letting of Government contracts has resulted in acute shortages of qualified research personnel. As the defense program progresses, it is likely that these shortages of highly trained personnel will become more acute. Science graduates with only the bachelor's degree will also find many good opportunities to enter professional work during the next few years.

The long-run outlook is good for earth scientists with graduate degrees. Petroleum and mineral prospecting will continue to be important, and earth scientists are likely to be concerned increasingly with many other problems of land and resource use and conservation, particularly those connected with water resources.

Geologists

The petroleum industry, which already employs over half of the Nation's geologists, needs still more of these scientists. The mining industry needs additional geologists to devise new and improved techniques for locating scarce mineral deposits in the United States and abroad. To stimulate a coast-to-coast search for minerals, the Defense Production Administration allocated $10 million last year to the Department of the Interior. This and other factors are creating greater employment opportunities for geologists, especially those fully trained, experienced, and ready to take charge of some aspect of geological research or exploration.

As the world's petroleum resources dwindle, geologists and other earth scientists will be called on to make systematic resurveys of oil-bearing regions, using improved techniques for locating oil deposits deep within the earth's crust. Exploration and exploitation of undersea areas for petroleum deposits have just begun. In exploration for uranium and other ores used in atomic fission, the utilization of geologists will undoubtedly increase, though the extent of the increase cannot be estimated at this time.

Geophysicists

The demand for geophysicists is closely related to the increased tempo of the world-wide search for petroleum reserves and mineral deposits needed in the defense program. Defense plans also call for more geophysicists for research in radioactivity and in cosmic and solar radiation.

Geophysicists use special techniques and instruments which yield information about earth structures many thousands of feet below the surface. These techniques are used not only in exploration for deposits but also in testing deep foundations before building and in making highly precise maps and charts of the earth's surface.

The future developments of the science of geophysics suggest a continuing demand for scientists in this field. Knowledge of the earth's interior through direct observation at widely scattered points extends to only about 3 miles of the 4,000 to the earth's center, and information on the ocean bed is very limited. It is therefore likely that the need for natural resources, now being rapidly depleted in the most accessible places, will necessitate the exploration of greater depths of the earth and ocean areas. Man's needs for water resources and flood control will also increase the demand for earth scientists.

In the interest of promoting the science of exploration geophysics each issue of *Geophysics* will contain a list of authors who wish to exchange reprints of their papers with those in other countries. All authors desiring to place their names and addresses on this list are requested to notify the business manager of the society.

EASTERN CANADA REGIONAL MEETING

The first regional meeting of the Society of Exploration Geophysicists to be held in Eastern Canada will convene at the King Edward Hotel, Toronto, October 27 and 28, 1952. The Eastern Regional Program Committee of S.E.G., under the direction of R. B. Ross, Gulf Research & Development Co., Pittsburgh, Pa., and Dr. Frank Press, Columbia University, New York City, is in charge of arrangements. General chairman of arrangements in Toronto is W. O. Cartier, of McPhar Geophysics Limited. The Canadian Society of Exploration Geophysicists, a local section of S.E.G in Calgary, Alberta, will assist the local committees. President of the Canadian Section is L. I. Brockway, of Gulf Research and Development Co., Calgary.

In announcing the meeting Mr. Ross said that problems of mining geophysics will be discussed, although some petroleum geophysics papers are scheduled. Present plans provide a schedule of morning and afternoon sessions on both meeting davs, allowing for presentation of as many as twenty-four technical papers. Earth scientists engaged in the application of geophysics to exploration for minerals have been invited to speak.

ANNUAL PACIFIC COAST MEETING

The New Statler Hotel, Los Angeles, has been chosen as headquarters for the 1952 annual regional meeting of the Pacific Coast Section of the Society of Exploration Geophysicists on October 30 and 31, it has been announced by Wallace L. Matjasic, of Honolulu Oil Corp., president of the Section, and chairman of arrangements for the S.E.G. As in the past, this will be a joint meeting of the Pacific Coast sections of the American Association of Petroleum Geologists, Society of Economic Paleontologists and Mineralogists, and the Society of Exploration Geophysicists. About 750 earth scientists engaged in exploration for oil are expected to attend, Mr. Matjasic said.

President of the Pacific Coast section of A.A.P.G. is Homer J. Steiny, of Tide Water Associated Oil Co., Los Angeles, and W. Thomas Rothwell, of Richfield Oil Corp., is president of the S.E.P.M. Section. T. H. Braun, of The Superior Oil Co., Pasadena, California, and Southern district vice president of the S.E.G. Pacific Section, is in charge of the technical program for geophysics. Mr. Matjasic stated that the morning session on Friday, October 31, will be devoted entirely to geophysical papers, and following luncheon on Friday there will be a joint session of A.A.P.G., S.E.P.M., an_ S.E.G. The annual joint dinner dance will be held at the Statler Hotel that evening. All sessions on Thursday, October 30, will be devoted to papers on geology and paleontology.

ANNUAL MIDWESTERN MEETING

Appointment of Richard Brewer, of The Atlantic Refining Co., Shreveport, as general chairman of the sixth annual midwestern meeting of the Society of Exploration Geophysicists has been announced by F. G. Knight, of Ohio Oil Co., president of the Ark-La-Tex Geophysical Society, Shreveport. The meet will be held November 13 and 14, 1952, in Fort Worth, Texas, Mr. Knight said, and will be sponsored by the Fort Worth, Dallas, Midland, Tulsa, and Shreveport local sections of the S.E.G with the Shreveport group in charge of arrangements.

Leslie C. Spencer, consulting geophysicist and secretary-treasurer of the Ark-La-Tex society, is chairman of the technical program committee for the meeting, and will be in charge of accepting papers for presentation. B. B. Burroughs, of Sunray Oil Co. and vice president of the Ark-La-Tex society, is chairman of the housing committee, and will be assisted by F. O. Mortlock, of Gulf Research and Development Co., Fort Worth. Other committee chairmen in Shreveport are Bryan Duby, of The Carter Oil Co., finance committee; Roy Fischer, consulting geophysicist, entertainment committee; and E. A. Malone, of Gulf Research and Development Co., registration committee.

AMERICAN GEOLOGICAL INSTITUTE

A meeting of the Board of Directors of the Institute was held on March 23rd just preceding the recent meetings in Los Angeles. Ten of the twelve member societies were represented.

Progress was reported on various activities of the Institute, including several which were mentioned in this section in the April number of *Geophysics*.

The career booklet, "Shall I Study Geological Science?" has been completed and the first printing of 5,000 copies has been distributed. A new printing of 5,000 has been ordered and requests are on hand for about 1,500 of these. This booklet is intended for the information of high school students, particularly seniors who are considering their college careers. If any of you wish to secure copies for high schools in which you are interested, they may be obtained from the Institute.

Work by the committee on a glossary of geological terms continues and 75,000 Key-sort cards have been ordered to which material from cards now in hand will be transcribed.

The journal of geological abstracts has progressed to the stage where it is planned to begin by photo-offset reproduction of abstracts in a monthly journal to be called "Current Abstracts in Geological Publications." A target date of October is now set for the first issue.

A cover has been designed and printed and a sample mock-up has been made for the professional magazine. It will be called "The Geological Record," to be published initially as a bimonthly. Solicitation of advertising has been started with a target date for Vol. I, No. 1, for Jan.–Feb., 1953.

The Institute is faced with a serious problem in the resignation of Dr. David Delo who has been its Executive Director since its activities began on June 1, 1949. Dr. Delo will become President of Wagner College, Staten Island, New York, and was expected to move there about July 15th.

There has been considerable misunderstanding about the affiliation of the American Geological Institute with the National Academy of Sciences and there is a widespread belief that this means that the Institute is connected in some way with the Federal government. The following letter from the President of the Institute explains the Academy and the National Research Council and points out that affiliation with them implies no connection whatever with the government.

AFFILIATION OF THE AMERICAN GEOLOGICAL INSTITUTE

"There is no truth whatever in the widespread misconception that because the A.G.I. is affiliated with the National Academy of Sciences-National Research Council it is also affiliated in some way with the federal government. Neither the Academy-Council nor the Institute is connected with the government.

"To be specific, the Academy is a top level independent society to which scientists are elected only after they have made outstanding contributions to scientific research. It now enrolls about 400 members and holds meetings at which scientific papers are presented. It occupies its own building which was built in 1923 with money provided by the Carnegie Corporation of New York, and the land on which the building was erected was purchased with private funds provided by private individuals.

"The Academy-Council receives no money by government appropriation. Entirely like many industrial corporations and universities, however, it does carry on contract work for government agencies but only if and when such agencies desire scientific advice on a subject which the Academy-Council is willing to consider. Like a college or university the Academy is also a corporation, and has an endowment invested in securities, most of it supplied by the Carnegie Corporation. It has also received a great deal of financial assistance from the Rockefeller Foundation, particularly for its program of post-doctoral fellowships which has been in operation for about 30 years. The Academy does have a federal charter, but such a charter is also held by the American Chemical Society as well as by several other similar organizations.

"The operating arm of the Academy is the National Research Council, established in 1916. It consists of a series of offices called Divisions, each devoted to a separate branch of scientific inquiry. The American Geological Institute is tied into the Council structure through the Division of Geology and Geography. All the geological and geophysical societies in the United States including the Society of Exploration Geophysicists are affiliated with the Division and appoint representatives to the Division for the transaction of its business. The Division works through committees which serve without pay, and the results of their work are issued in the form of reports. The work of one of these committees during the 1920's, under the leadership of K. C. Heald, Everett DeGolyer and other

geologists prominent in the oil industry, led to the present American Petroleum Institute program of research into the origin of petroleum.

"In addition to the Divisions, the Research Council has other special offices. One of these is the Building Research Advisory Board, which is supported by the private building industry with a view toward securing advice as to the direction which its own research should take.

"Because they can call on the services of prominent scientists throughout the country it is only natural that the Academy and Council are constantly asked for scientific advice by the government, the Armed Services, industry, and other agencies. When the government asks for advice, it does so through a contract, of almost exactly the same type as the contract which would be written with an industrial corporation for a research and development project. These contracts pay the salaries of full-time administrators (when these are necessary), the expenses (but no salary) for committee members, and an overhead charge for business office expense. Selection of committee members and the nature of advice given, or nature of reports rendered, have always been zealously guarded by the Council as its prerogatives because only in this way can it render objective decisions as a private organization.

"After the American Geological Institute was first proposed during the A.A.P.G. Annual Meeting at Fort Worth in 1943, there was a period of several years of discussion. The geological and geophysical societies involved finally decided to establish the Institute at the National Research Council not only because it represented "neutral ground," but also because it was willing to provide financial assistance. Not only at that time, but unfortunately at present, insufficient funds are provided by the geological profession to support the Institute; thus about 25% of its annual expenses have been and now are provided indirectly by the Research Council. This support does not restrict the activities of the A.G.I., however, and the Institute has the advantage of being in a location where it can keep abreast of national developments which may affect the geological profession.

"I regret that it seems necessary to emphasize again that the National Research Council does not in any way dictate to the Institute in the expenditure of its funds, the appointment of Directors or committee members, or the character of its program. All these and other cognate matters are decided solely by the member societies either directly, or through their appointed representatives on the Board of Directors."

Carey Croneis, President
American Geological Institute

VENEZUELAN GEOPHYSICISTS ORGANIZE

Forty three exploration geophysicists met in Caracas, Venezuela, to form the "Sociedad Venezolana Geofisica" (Venezuelan Geophysical Society) on May 26, 1952. The group voted unanimously to form the society along the same lines and for the same purpose as the S.E.G. Regular meetings will be held for the discussion of current exploration problems encountered in Venezuela, and consideration will be given to affiliation at a later date as a local section of the S.E.G.

W. C. Merritt, of Creole Petroleum Co., was named chairman of the constitution committee. Other members of the committee are Dr. Eduardo Rohl, Dr. A. Romero, C. F. Wachter and R. R. McIlwaine; and the following S.E.G. members in Caracas: J. E. Dorris, of Seismograph Service Corp. of Dela., H. Pearson, of Shell Caribbean Petroleum Co., R. E. McMillen, of Phillips Venezuelan Oil Co., and T. A. Kibby, of Gulf Research & Development Co.

EXPLORATION COMPANIES SPONSOR EARTHQUAKE SEISMOGRAPH

Donation of $25,000 by four geophysical exploration companies toward establishment of an earthquake seismograph station at The Rice Institute, Houston, Texas, has been announced. The gift was made by General Geophysical Co., Independent Exploration Co., Robert H. Ray Co., and Seismic Explorations, Inc. all of Houston. These consulting geophysical companies, although engaged primarily in the application of seismology to the search for oil, have shown vital interest in the basic earth sciences and feel that the establishment of such a station at Rice will be of great value

in fundamental research and will contribute to the solution of geophysical problems.

The money will be used to provide the equipment for a seismological station for the continuous recording of the movement of the earth and earthquakes anywhere in the world. It will be the first such station to be established in the Houston area, and in cooperation with other stations such as those at the California Institute of Technology in Pasadena and at Saint Louis University will make possible the directional plotting of earth waves. The Rice Institute will thus become a part of the great scientific network which serves to gather information for peoples all over the world on the incidence, direction, and violence of earth tremors and quakes.

In accepting the gift, President William V. Houston, of The Rice Institute, emphasized that the seismograph will serve as a most important auxiliary feature of the geological work soon to be undertaken through the Harry Carothers Wiess Chair of Geology. Decisions as to the nature of the equipment to be purchased with the gift and as to the operation of the station will be deferred pending the selection of the Harry Carothers Wiess Professor of Geology. It is believed, however, that work can be started in setting up the station at the same time as the establishment of the geological courses at the Institute.

"The presentation of such gifts as these," said President Houston, "in conjunction with the funds made available by Mrs. Wiess, will make it possible to create in the Houston area a center of geophysical study of world-wide importance."

RESEARCH, FELLOWSHIP GRANTS RENEWED BY SHELL OIL COMPANY FOR 1952–53

An increase of approximately 25 per cent in grants for fellowships, stipends, and research expense allowances was announced by the Shell organization as part of its renewal for the 1952–53 academic year of its programs in support of higher education.

A series of annual fundamental research grants initiated in 1950 will be continued at a cost of $60,000. This part of the program remains unchanged. However, the 45 graduate fellowships will receive a total of $95,000 this year, as compared with $75,000 previously.

The research grants are made directly to university science departments to assist them in conducting basic research. Twelve grants of $5,000 each have been made in the fields of chemistry, chemical engineering, geology, mechanical engineering, metallurgy-corrosion, and physics. Schools receiving these awards are California Institute of Technology, Carnegie Institute of Technology, University of Chicago, Harvard, Massachusetts Institute of Technology, Yale, Stanford and Princeton. There are no restrictions on publication of the results, nor on the way the money is spent provided it is used directly for fundamental research in the field designated.

In recent years, industry has become increasingly aware of the value of extending aid for basic research, realizing that national defense and continued progress in industry are both vitally dependent on the advancements of science. The Shell program was established in recognition of the fact that although colleges and universities are well equipped to carry on such research, they are often handicapped by lack of the necessary funds.

Shell's graduate fellowship program is designed to help outstanding students obtain advanced scientific degrees. It provides awards to universities in the fields of chemistry, chemical engineering, geology, geophysics, mechanical engineering, petroleum production engineering, physics, and plant science.

Students recommended by the colleges as Shell fellows receive a stipend of $1,500 for the academic year, plus payment of tuition and fees, and the school receives $400 for related research expenses of the fellow. Last year's awards were $1,200 for the stipend and $300 for research expenses. Candidates in the final year of doctorate study are given preference, but awards may be made to other graduate students. Recipients of these grants are under no obligation to Shell.

Both the fellowship and the basic research programs are administered by the Shell fellowship committee, made up of senior executives representing Shell Oil Company, Shell Chemical Corporation, Shell Development Company, and Shell Pipe Line Corporation.

ANNOUNCEMENT OF SAFETY COMMITTEE

The following Questionnaire has been submitted to individuals in charge of geophysical operations. The questions were prepared and suggested by all members of the Committee on Safety.

The Committee on Safety of the S.E.G. was established over a year ago by the Council of the Society to promote and further the interests of safety and accident prevention in the geophysical industry. To obtain a better idea on what we of the Safety Committee might do to further this cause, we are submitting the enclosed Questionnaire to you.

Will you or someone in your organization fill in the requested information and return it to us in the enclosed self-addressed and stamped envelope at your earliest convenience. It is not necessary that this Questionnaire be signed showing the name of the company supplying the information.

Very truly yours,
BART W. SORGE, *Chairman*

SAFETY AND ACCIDENT PREVENTION QUESTIONNAIRE

1. NUMBER OF CREWS OPERATING

   Under 5 _____; 5 to 20 _____; 20 to 40 _____; over 40 _____.
2. SAFETY AND ACCIDENT PREVENTION EFFORT

   Active _____; occasional safety effort _____; no definite activity _____.
   Remarks:

3. SAFETY ENGINEER

   Full time _____; part time _____; none _____.
4. SAFETY AND ACCIDENT PREVENTION POLICY SET BY

   Owner _____; management committee _____; supervisors _____; party chiefs _____; all employees _____; none _____.
   Remarks:

5. RECORDS OF ACCIDENTS
   We keep complete records of all accidents _____; records for insurance purposes only _____; no records _____.
6. WE (DO _____ DO NOT _____) MAINTAIN FREQUENCY AND SEVERITY INFORMATION TO CHECK ON OUR SAFETY PERFORMANCE.
7. SAFETY POSTERS AND BULLETINS

   We distribute them regularly _____; occasionally _____; not at all _____.
8. INTEREST IN SAFETY AND ACCIDENT PREVENTION

   We feel that these efforts are very important _____; should be a by-product of good party operation _____.

9. SUBMITTING INFORMATION TO RECOGNIZED SAFETY AUTHORITIES

A.P.I. (Yes _____ No _____); Bureau of Mines (Yes _____ No _____); National Safety Council (Yes _____ No _____).

10. TO ENCOURAGE SAFETY AND ACCIDENT PREVENTION WE (DO _____ DO NOT _____) GIVE OUR FIELD PARTIES REWARDS FOR ACHIEVEMENT. IF YOU DO, PLEASE EXPLAIN NATURE OF AWARD.

YOUR OPINION AS TO THE EFFORTS AND ACTIVITIES OF THE S.E.G. COMMITTEE ON SAFETY WOULD BE APPRECIATED.
Remarks:

11. SAFETY COMMITTEE ACTIVITIES

We believe the Committee should expand its activities _____; proceed as at present _____; its activity not necessary _____.

12. SAFETY POSTERS

We would like to see the distribution expanded _____; continued as at present _____; discontinued _____.

13. SAFETY BULLETINS AND BOOKLETS

We would like to see the Committee publish and distribute these _____; prefer to have individual companies handle this problem _____.

14. WOULD YOU FAVOR THE KEEPING OF MONTHLY ACCIDENT STATISTICS BY THE SAFETY COMMITTEE OR S.E.G. BUSINESS OFFICE? (YES _____ NO _____)

15. WOULD YOU FAVOR A PERIODIC ANALYSIS OF ACCIDENT TRENDS WITHIN THE GEOPHYSICAL INDUSTRY? (YES _____ NO _____).

IMPORTANT ANNOUNCEMENT OF ADVISORY COMMITTEE ON RADIOACTIVE MINERAL EXPLORATION

On June 5, at Denver, Colorado, delegates appointed by the presidents of A.A.P.G., S.E.G., and S.E.P.M. organized a committee to be known as the "Advisory Committee on Radioactive Mineral Exploration." This committee is jointly sponsored by the three societies above named.

The following statement was drawn up at the Denver meeting:

SEARCHING FOR RADIOACTIVE MINERALS IN ROUTINE EXPLORATION FOR OIL AND GAS

1. *Urgency for expanded exploration for radioactive minerals in the United States.*—In view of the increasing importance of radioactive minerals, and in particular of uranium ores, as a source of atomic energy, especially for purposes of national defense, it is urgent that no opportunity be overlooked nor neglected for widespread alertness for evidences of such minerals. Not only is there need for discovering more occurrences of these minerals, but also there is need for more information on their distribution in areas where they are already known to be present.

2. *Coincidence of areas explored for petroleum and areas prospective for uranium ores.*—It so hap-

pens that in many regions where oil and gas are sought, ores of uranium may occur. This is especially true of extensive areas in the Rocky Mountain Province and in the western part of the Central Plains Province. There are many deposits of carnotite (a common uranium ore) in the Plateau Province of southeastern Utah and the adjoining corners of Colorado, New Mexico, and Arizona, and recently deposits of uranium minerals have been found in the Powder River Basin in Wyoming. In these same areas, and in many others where uranium ores *may* occur, exploration for petroleum is being carried on aggressively by numerous companies. Therefore, it is suggested that these companies be encouraged to take steps to combine with their petroleum exploration a moderate effort at exploration for radioactive minerals.

3. *Advisory Committee on Radioactive Mineral Exploration.*—Within the membership of the American Association of Petroleum Geologists (A.A.P.G.), the Society of Exploration Geophysicists (S.E.G.), and the Society of Economic Paleontologists and Mineralogists (S.E.P.M.), a committee has been organized, to be known as the Advisory Committee on Radioactive Mineral Exploration.

4. *Functions and Policies of the Committee.*—This committee, as its name implies, will serve only in an advisory capacity. Its primary functions are:

a. To invite those who may be inclined or interested, to investigate the feasibility of their carrying on exploration for radioactive minerals along with their petroleum exploratory efforts;

b. To give advice as to how and where such exploration for radioactive minerals may be conducted, if desired;

c. To advise where information can be obtained concerning the search for radioactive materials;

d. To endeavor to keep abreast of what is going on in this search for radioactive materials; and

e. To encourage the preparation and presentation of papers on the subject of exploring for useful radioactive minerals.

This committee will concern itself with over-all encouragement of participation of the oil and gas industry in exploration for radioactive minerals and will deal with the broad aspects and policies of such a relationship. It will not be too much concerned with detailed techniques, problems of instrumentation, methods, and processes for detailed surveys, nor with any of the technical aspects of the program which may better be handled by specialists. In no way will it suggest unified cooperation, or cooperative procedure, between organizations for the conduct of radioactive mineral exploration. Its whole objective is to stimulate an interest in the search for radioactive minerals, occurring within feasible mining depths, when and where petroleum exploration is in progress.

5. *Suggestions regarding radioactive mineral exploration.*—The oil companies, consulting firms, and others engaged in petroleum exploration can function in exploring for radioactive minerals.

(a) by observations with Geiger counter on outcrops where surface mapping is in progress;

(b) by holding out, for special study, those gamma-ray logs which reveal "kicks" stronger than the normal "kicks" known to be associated with the Chattanooga shale or similar highly radioactive shales;

(c) by Geiger-counter or scintillation-counter examination of cuttings from seismic shot holes; and

(d) by similar examination of the cuttings from approximately the upper 500 feet of holes drilled for oil or gas or drilled as exploratory core holes, "slim holes," or "stratigraphic test holes."

(A few remarks may be made here on paragraphs (b), (c), and (d) under 5. When gamma-ray logs show abnormally high "kicks," they may be indicating the presence of radioactive ores at depths too great for exploitation. Such logs may be of value either (1) where they reveal high radioactivity in formations known to be highly radioactive at or near their outcrop, because this suggests wide distribution of such radioactivity, or (2) where by revealing high radioactivity at considerable depths, they suggest that search should be made for indications of similar high radioactivity in the same formations at or near the outcrop of these formations.

Under present prices and conditions, 500 feet is probably as deep as uranium mineral can be profitably mined; hence, the mention of 500 feet in 5 (d).)

6. *Utilization of evidences of radioactive minerals.*—If and when evidences of possible economic radioactive minerals is found, the discoverer is free to determine his own course of action. If desired, he could investigate the possibility of mining on his own account; or he could sell his rights, probably on a royalty basis, to some outside mining concern.

7. *Conclusion.*—On the basis of the foregoing, the committee suggests that those engaged in petroleum exploration carefully consider including, in the course of their normal exploration activities their own program of prospecting for radioactive minerals.

Additional information can be obtained by writing to the chairman of the committee.

Present membership of the Advisory Committee on Radioactive Mineral Exploration is as follows:

Frederic H. Lahee, *Chairman*
John Emery Adams
John G. Bartram
Henry C. Cortes
Cecil H. Green
Sigmund Hammer
Gerhard Herzog
Morton T. Higgs
J. Harlan Johnson
A. I. Levorsen
Clarence L. Moody
Gerald H. Westby

The committee will be glad to endeavor to answer questions and give advice within the scope of its functions.

INTERNATIONAL PETROLEUM EXPOSITION

Tulsa, Okla.—About $100,000 is being spent on renovation and repair of the International Petroleum Exposition grounds for the 1953 oil show. Also, 35,000 square feet of additional exhibition grounds are being prepared for the May 14–23 display.

William B. Way, exposition general manager, said the additional space will include four 20-foot streets, three walkways, each 12 feet wide, and a 40-foot loading zone to facilitate handling of heavy equipment to be displayed. This area will be ready for exhibitors Nov. 1.

Way said the renovation program includes many new roofs, new sewer and gas lines, replacement of worn electric wiring, landscaping.

IPE President W. G. Skelly said invitations to attend the oil show have been sent to all oil producing nations of the world and to their oil industry executives. The actual invitations are being issued by the U. S. department of state and the NOMADS, an organization of men who sell oil field equipment in foreign countries.

To give the oil show an additional official international flavor, Oklahoma's Governor Johnston Murray toured the oil centers in the Carribean and Central and South America. He personally extended invitations signed by himself and President Skelly.

The governor's tour took him to Cuba, Santo Domingo, Aruba, Trinidad, Puerto Rico, Venezuela, Brazil, Uruguay, Argentina, Chile, Bolivia, Peru, Ecuador, Colombia, Panama, Mexico and Costa Rica.

For the benefit of the foreign representatives, the NOMADS will give a banquet during the show. These visitors are being asked to register at the NOMADS building on the exposition grounds. The NOMADS also will provide them with transportation and serve as hosts for the run of the show.

General Manager Way said the show expects to attract 20,000 oil firm representatives from every state in the union and from 50 foreign nations. The 1948 oil exposition drew more than 15,000 oil men from every oil producing state in the union and from 43 foreign nations.

When the dates setting the oil exposition were announced, more than 500 reservations for space were made almost immediately, President Skelly disclosed. In all, about 1,000 exhibitors are expected for the $100,000,000 oil exposition in this oil capital of the world.

S.E.G. TO OFFER TWO DISTINGUISHED LECTURE TOURS DURING 1952–53 SEASON

The S.E.G. Distinguished Lectures Committee has been most fortunate in securing two outstanding speakers to lecture before the various local geophysical societies during the 1952–53 season. During late November and early December, Dr. J. Tuzo Wilson, Professor of Geophysics at the University of Toronto, will be available for a lecture on the use of geophysics as a tool for studying the origin of continents and mountain systems. During January and February, Dr. Maurice Ewing, Professor of Geology at Columbia University and Director of the Lamont Geological Observatory, will make a six-week Distinguished Lecture tour under the joint sponsorship of the S.E.G. and the A.A.P.G. Dr. Ewing's subject is "The Atlantic Ocean and Its Margins." This lecture is being offered to all local sections both of the S.E.G. and A.A.P.G., but it is expected that a single jointly-sponsored meeting can be arranged in each city where both national societies have local groups.

Dr. Wilson received his M.A. at Cambridge University in England and his Ph.D. in geology at Princeton. For many years he has been investigating the origin and structure of the Canadian shield by correlation of geophysical evidence with geological observations. From these studies he has developed some new theories on the origin of continents and mountain systems. During the past few years he has published papers on his work in American, British, and Canadian scientific journals.

Dr. Ewing received his A.B., M.A., and Ph.D. degrees, all in Physics, at Rice Institute. Over the past two decades he has made substantial contributions to virtually every phase of geophysics. His specialty has been the study of the formations below the continental shelves and ocean basins. He was the pioneer in offshore seismic exploration, having carried on a successful refraction survey in the Atlantic as early as 1935. He and his associates at Columbia are now engaged in a long-range program to study the geology beneath the Atlantic Ocean by seismic, gravity, and core-sampling techniques.

The Distinguished Lectures Committee is at present working with the presidents of the various local sections to arrange itineraries and schedules for these two lecture tours.

MILTON B. DOBRIN
Chairman, Distinguished Lecture Committee

ANNOUNCEMENT

JOINT ANNUAL MEETING

SAM HOUSTON COLISEUM, HOUSTON, TEXAS, MARCH 23–26, 1953

AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS
SOCIETY OF EXPLORATION GEOPHYSICSTS

The joint annual meeting of the three petroleum exploratory societies will be held at the Sam Houston Coliseum, Houston, Texas, on March 23, 24, 25, and 26, 1953.

All requests for hotel rooms should be made by returning the attached form to the *A.A.P.G. Hotel and Housing Committee, Attn: Olin G. Bell, Chairman, Post Office Box 2180, Room 955½, Humble Building, Houston 1, Texas.* Requests for reservations should be made as far in advance of February 23, 1953, as possible, and should contain all information requested on the attached form. Receipt of requests will be acknowledged and filed in order of receipt by the Hotel and Housing Committee. Actual assignments will be made in the various hotels and confirmations will be mailed about 60 days prior to the convention. Members who request reservations, but later find they can not attend should notify the Hotel and Housing Committee without delay. Blocks of rooms will not be reserved. All rooms must be reserved in the names of individuals.

This notice is being mailed simultaneously to the members of the three societies. Officers, chairmen, and committee members, particularly, are requested to reply promptly.

THE EXECUTIVE COMMITTEES

Tulsa, Oklahoma
October 1, 1952

APPLICATION FOR HOUSING ACCOMMODATIONS
HOUSTON, TEXAS

March 23–26, 1953

Joint Annual Meeting of
A.A.P.G., S.E.P.M., S.E.G.

For your convenience in making hotel reservations for the coming joint meeting of the American Association of Petroleum Geologists, the Society of Economic Paleontologists and Mineralogists, and the Society of Exploration Geophysicists, March 23–26, 1953, in Houston, hotels and their rates are listed below.

Hotel space in first-class downtown hotels is limited in Houston. There are, however, several good hotels down town and several first-class semi-residential type hotels out from the center of town in which accommodations have been blocked for this meeting. In addition, there are some excellent motels and tourist courts located on or immediately adjacent to the principal highways in Houston in which space has been reserved. Space for convention members has also been reserved in two excellent hotels in Galveston. A four-lane super highway makes Galveston easily accessible for the convention. Special buses for convention members will be available at the time, or those preferring to use their cars may do so. The distance is fifty miles and can be made with ease and safety in one hour.

In requesting reservations use the form at the bottom of this page, indicating your first, second, and third choices. Because of the limited number of single rooms available, you will stand a much better chance of securing accommodations if your request calls for rooms to be occupied by two or more persons. All reservations must be cleared through the A.A.P.G. Hotel and Housing Committee. *All requests for reservations must give definite date and hour of arrival as well as definite date and approximate hour of departure; also names and addresses of all persons who will occupy reservations* must *be included.*

	Single	For Two Persons		Suites
	One Person	Double Bed	Twin Beds	
Houston:				
*Rice	$4.50–$ 8.50	$6.50–$10.50	$8.00–$11.00	$16.00–up
*Lamar	4.00– 8.00	6.00– 10.00	7.50– 12.00	14.00–$28.00
*Texas State	4.00– 9.00	6.00– 12.00	7.00– 12.00	9.50–up
*Sam Houston	3.25– 4.00	4.50– 5.50	6.00– 8.00	
*Wm. Penn	3.75– 5.00	5.00– 6.25	7.00–	
*Ben Milam	3.75– 5.00	4.00– 5.00	7.00– 9.00	15.50–up
Shamrock	6.00– 16.00	8.00– 18.00	8.00– 18.00	25.00– 55.00
Other Good Houston Hotels	2.50– 6.00	3.75– 8.00	6.00– 9.00	8.00–up
Galveston:				
†Galvez	3.50– 10.00	5.75– 8.00	6.50– 9.25	12.50– 35.00
†Buccaneer	3.50– 10.00	5.75– 8.00	6.50– 9.25	12.50– 35.00
Motels: Houston	3.00– 6.00	5.00– 8.00	6.00– 10.00	10.00–up

* Downtown Hotel.

† On Seawall.

In the event that the hotel room rate structure is changed prior to the above convention, these rates will be changed accordingly.

ALL REQUESTS FOR RESERVATIONS MUST BE RECEIVED PRIOR TO FEBRUARY 23, 1953

A.A.P.G. Hotel and Housing Committee
Attn: Olin G. Bell, Chairman
Post Office Box 2180, Room 955½, Humble Building
Houston 1, Texas

Please reserve the following accommodations for the Joint Convention of the A.A.P.G., S.E.P.M., and S.E.G., in Houston, Texas, on March 23–26, 1953.

Single Room _____ Double Bedded Room _____ Twin Bedded Room _____

2 Room Suite _____ Other Type of Room _____

Rate: From $_____ to $_____ First Choice Hotel _____

Second Choice Hotel _____

Third Choice Hotel _____

Motel in Houston _____

Hotel in Galveston _____

Arriving at Hotel (date) _____ Hour _____ A.M. _____ P.M.

Leaving (date) _____ Hour _____ A.M. _____ P.M.
I (will) (will not) have the use of a car while in Houston.

THE NAME OF EACH HOTEL GUEST MUST BE LISTED. Therefore, please include the names of *both* persons for *each* double room or twin bedded room requested. Names and addresses of all persons for whom you are requesting reservations and who will occupy the rooms asked for: _____

_____

_____

(Individual Requesting Reservations)

Name _____

Address _____

Company Affiliation _____

Would you be interested in attending an Alumni Luncheon?

_____ What School? _____

_____

If the hotels of your choice are unable to accept your reservation, the Hotel and Housing Committee will make as good a reservation as possible elsewhere provided that all hotel rooms available have not already been taken.

ANNOUNCEMENT OF NEW PUBLICATION

A Guide to Tables of the Normal Probability Integral, National Bureau of Standards Applied Mathematics Series 21, iv, 16 pages, 15 cents (order from Government Printing Office, Washington 25, D. C.).

This guide provides a ready desk reference for the research worker or student who frequently uses the normal probability tables. It includes the important sources of tables likely to be accessible in libraries of universities and research organizations and suggests as well some of the more recent publications which are of considerable value to technical libraries and students of statistics.

The enormous impetus accorded in recent years to statistical theory and application has emphasized the need for a variety of tables of statistical functions. Foremost among these functions and of fundamental importance is the normal probability function, which has been more widely tabulated than any other function and which appears in many different forms and nomenclatures.

This small and concise volume facilitates reference to those tables containing the particular form of the function sought by users of the various tables of the normal probability integral given in standard statistical texts and various handbooks. Each listing is preceded by an illustration and key intended to clarify the terminology used in each case and to explain exactly what the tabulated entries represent.

Of the guide's two main parts, the first gives the sources and essential characteristics of tables for the indicated types of segments of area under the normal curve. It also contains a description of interpolation methods that are especially applicable and brief comments showing the relationship between some types of normal tables and other tabulated functions. The second part consists of a bibliography of the sources referred to in the first part.

(Note: Foreign remittances must be in U. S. exchange and should include an additional one-third the publication price to cover mailing costs.)

FOREIGN EXCHANGE OF REPRINTS OF GEOPHYSICAL PAPERS

Listed below are the names and addresses of geophysicists who have expressed the desire to cooperate in the exchange of reprints between authors of geophysical papers in America and abroad.

DR. HANS V. HELMS, Geophysicist, Hannover, Germany, Goldener Winkel 4I.

PROF. CARLO MORELLI, Osservatorio Geofisico Trieste II, Italy.

In the interest of promoting the science of exploration geophysics each issue of *Geophysics* will contain a list of authors who wish to exchange reprints of their papers with those in other countries. All authors desiring to place their names and addresses on this list are requested to notify the business manager of the society.

OUT-OF-PRINT ISSUES OF *GEOPHYSICS* AVAILABLE

The Geophysics Library of the Imperial College of Science, London S.W. 7, England has duplicate copies of *Geophysics*, Vol. III, Nos. 1 and 3; Vol. V, No. 1; and Vol. IX, No. 2. The librarian would be willing to exchange one or more of these for Vol. X, No. 2.

GEOPHYSICAL SOCIETY OF OKLAHOMA CITY ORGANIZED

Sixty-two exploration geophysicists in the Oklahoma City area have organized the Geophysical Society of Oklahoma City. Richard M. Davis, of the Carter Oil Co., who was appointed temporary chairman of an organizing committee by a group of Oklahoma City earth scientists last spring, invited all geophysicists in the area to attend a dinner meeting held in the Y.M.C.A. Monday, September 8, 1952. Assisting Davis in laying plans for the meeting was Lynn B. Trombla, president of Central Exploration Company, Oklahoma City, who served as temporary secretary of the committee. Davis said the increasing prominence of Oklahoma City as a center of oil exploration activity and geophysical research through establishment of exploration departments there by several major oil companies has brought a large number of oil finders to the capital city, and independent consulting geophysicists have established a number of contracting firms in the area. Quoting from the constitution which has been prepared for adoption by the new society, Davis stated, "The object of this society is to promote the science of geophysics and to promote fellowship and cooperation among those persons interested in geophysics." These objects are to be accomplished through holding regular monthly meetings at which members of the society and other leading exploration scientists will present technical papers for discussion, as well as occasional social events.

Upon adoption of the constitution, the organizing committee circulated among the charter members a petition for affiliation as a local section of the Society of Exploration Geophysicists, national group of exploration scientists. The petition has been submitted to the S.E.G. Executive Committee.

FIRST OFFICERS OF THE OKLAHOMA CITY SECTION

Front row, left to right: Richard M. Davis, president; George V. Dunn, first vice-president; and Erik Thomsen, treasurer. Back row, left to right: Arnold Bleyburg, alternate district representative; Paul M. Warren, second vice-president; James Finley, secretary; and John Hill, district representative.

Guests at the meeting included Paul L. Lyons, of Anchor Petroleum Co., president of the Geophysical Society of Tulsa and editor of *Geophysics;* Dal Davis, of Industrial Electronic Supply Co., secretary of the Tulsa section; E. V. McCollum, of E. V. McCollum & Co., district representative from the Tulsa Section; and Colin Campbell, business manager of the Society of Exploration Geophysicists with headquarters in Tulsa.

A slate of nominations for officers of the new society was presented by the organizing committee,

CHARTER MEMBERS OF THE OKLAHOMA CITY SECTION

These sixty-two geophysicists from Oklahoma City, Shawnee, Clinton, Anadarko, and Ardmore, Oklahoma met in Oklahoma City on September 8, 1952 to organize the Geophysical Society of Oklahoma City, and to petition for affiliation as the tenth local section of the S.E.G.

including Lynn D. Ervin, of Stanolind Oil & Gas Co., and R. M. Davis, of The Carter Oil Co., for president; Glenn Lambert, of Shell Oil Co., and George Dunn, of Stanolind Oil & Gas Co., for first vice president; Paui Warren, of Continental Oil Co., and Duff Roberts, of Sohio Petroleum Co., for second vice president; Wes Seifert, of Magnolia Petroleum Co., and James Finley, of Continental Oil Co., for secretary; Eric Thomsen, of Stanolind Oil & Gas Co., and H. C. Talley, of Sohio Petroleum Co., for treasurer; and John Hill, of The Carter Oil Co., and Arnold Bleyburg, of Gulf Oil Corp., for district representative to the S.E.G.

The first official meeting of the new society is scheduled for Monday, October 30, at the Y.M.C.A.

PERSONAL ITEMS

HOWARD E. ITTEN, formerly division geophysical supervisor for Stanolind Oil & Gas Co., Fort Worth, announces the formation of Empire Geophysical, Inc., of which he is president, at 3615 West Sixth Street, Fort Worth, Texas.

ROBERT M. DREYER has been granted a leave of absence from his duties as Professor of Geology and Geophysics at the University of Kansas to accept a position as geologist in charge of the uranium division of Kerr-McGee Oil Industries. Professor R. C. Moore will assume the departmental chairmanship at the University.

JAMES K. ZIEGLER has been elected vice-president in charge of Century Geophysical Corporation of Canada, a wholly-owned subsidiary of Century Geophysical Corp., Tulsa, Oklahoma. Mr. Ziegler was formerly manager in charge of Canadian operations for Century, and his address remains 233 Examiner Building, Calgary, Alberta.

LEMAN MILTON HOLLEY and JENNINGS G. SMITH are recipients of one-year associate memberships in the S.E.G. presented by the Geophysical Society of Tulsa in June of this year. The action came in recognition of scholastic achievement. The men were the two top members of the class in geophysics graduating from the University of Tulsa in June.

Holley has joined Schlumberger Well Surveying Corp. as engineering trainee, and Smith has joined Western Geophysical Co., as party chief.

COL. MERLE C. BOWSKY has been appointed Chief of Staff at U. S. Army SW Signal Corps Training Center, Camp San Luis Obispo, California.

D. H. SCOTT has been appointed head of the gravity staff in the Houston geophysical office of The Texas Company, transferring from the Pacific Coast division where he was supervisor of geophysical operations. Mr. Scott will be succeeded by T. H. BRAUN, of the Superior Oil Company, as Vice President, Southern District, of the Society of Exploration Geophysicists, Pacific Coast Section.

GERALD H. WESTBY, president of Seismograph Service Corp., Tulsa, was a guest at the London Meeting of the European Association of Exploration Geophysicists May 22 and 23 at Manson House.

SHELLEY KRASNOW, president of Gerator Corporation, Arlington, Virginia, announces formation of the Geophysical Exploration Division of the company. E. R. Shepard, formerly in charge of geophysical foundation exploration, Army Corps of Engineers—U. S. Bureau of Public Roads, will supervise the new division. Mr. Krasnow will retain supervision of well-logging and special electrical investigations.

CECIL H. GREEN announces that a seismic exploration conference was conducted in Mexico City August 21 and 22, 1952 under the joint auspices of Petroleos Mexicanos and Geophysical Service Incorporated. The conference was well-attended by personnel of the two organizations as well as by members of the petroleum exploration industry resident in Mexico. Various papers were presented pertaining to geophysical exploration in general and activities in Mexico in particular. Guest speaker at a special evening session was Dr. M. King Hubbert of Shell Oil Company, Houston, who delivered

a paper on "Entrapment of Petroleum Under Hydrodynamic Conditions." S.E.G. members who prepared papers for the conference included Ing. Antonio Garcia Rojas, Ing. Manuel Alvarez, Jr., both of Petroleos Mexicanos; and Cecil H. Green, G. J. Kohler, P. E. Haggerty, D. W. Rockwell, B. A. Harris, J. W. Thomas, H. B. Peacock, E. J. Stulken, and K. E. Burg of the GSI organization. Other speakers from Pemex were Senator Antonio J. Bermudez, Director General; Sr. Ing. Manuel Rodriguez Aguilar, Exploration Manager; and Ing. Jesus Basurto.

R. B. CARTER, formerly party chief with Gulf Research & Development Co. at Vernal, Utah, has been transferred back to the research laboratories at Pittsburgh, Pennsylvania, where he is now acting as geological coordinator for the airborne magnetometer work.

JAMES D. DIVELBISS has become chief geophysicist for the Chicago Corporation, Continental Life Bldg., Fort Worth, Texas. H. M. COOPER, formerly with Deep Rock Oil Corp., has replaced Mr. Divelbiss, and is now in charge of the Denver, Colorado office of the Chicago Corporation at 528 Symmes Building.

WALTER H. AMIS, vice-president of National Geophysical Co., has announced the appointment of J. H. Frasher to the position of assistant vice-president with National Geophysical Co. of Canada, Ltd. Mr. Frasher began his employment with National in January, 1946, and has advanced to his present position through those of party chief and supervisor of field parties.

SIDON HARRIS, president of Southern Geophysical Co., has announced the addition of R. E. GATHINGS and K. C. VAN ORDEN to the supervisory staff of his company. Mr. Gathings has resigned as vice-president and supervisor of Southwestern Consultants, Inc., and has joined Southern in California. He is a graduate of Sewanee University with a major in physics, and his geophysical experience has been in West Texas, New Mexico, and the Rocky Mountains. Mr. Van Orden has been in geophysical work for ten years, operating in Texas, Oklahoma, Kansas, Colorado, and Canada. He holds the B.S. degree in mathematics from Macalester College, St. Paul, Minnesota. He is stationed in the San Juan Basin of Colorado under ELMER F. BLAKE, vice-president in charge of the company's Rocky Mountain division, Denver, Colorado.

SOCIETY OF EXPLORATION GEOPHYSICISTS
CONSTITUTION

Article I. Name
Article II. Object
Article III. Membership
Article IV. Code of Ethics
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Article VIII. Council
Article IX. Executive Committee
Article X. Meetings
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Article XV. Business Manager
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CONSTITUTION

(As amended to August 26, 1948)

Article I. Name

Section 1. The Society shall be called the "Society of Exploration Geophysicists."

Article II. Object

Section 1. The objects of this Society shall be to promote the science of geophysics especially as it relates to exploration and research, to foster the common scientific interests of geophysicists, and to maintain a high professional standing among its members.

Article III. Membership

Section 1. The membership of this Society shall consist of persons elected and qualified in accordance with the Constitution and Bylaws of this Society at the time of such election.

Section 2. The membership of this Society shall consist of Honorary Members, Active Members, Associate Members, and Student Members.

Section 3. To be eligible to election to Honorary Membership a person shall, in the unanimous opinion of the Standing Committee on Honors and Awards and the Council, have made a distinguished contribution to geophysics or a related field which warrants exceptional recognition.

Section 4. To be eligible to election to Active Membership an applicant must have been actively engaged in practising or teaching geophysics or a related field for not less than eight years (up to four years as a student in a recognized college or university may be counted toward this total) of which at least three years must have involved work of a responsible nature calling for independent judgment and the application of geophysical or geological principles.

Section 5. To be eligible to election to Associate Membership, an applicant must be actively interested in geophysics.

Section 6. To be eligible to election to Student Membership an applicant must be a graduate or undergraduate student in good standing in residence at a recognized university or college.

Section 7. An Honorary Member or Active Member shall enjoy all privileges of the Society. He shall be eligible to hold any office, to vote on all matters submitted to the membership, to petition the Council or Executive Committee on any matter, to sponsor applicants for membership and to publish his affiliation with the Society.

Section 8. An Associate Member or Student Member shall be entitled to attend the meetings of the Society, to receive its Journal and to purchase its publications, on the same terms as an Active Member. He shall have none of the other privileges of membership and in publishing his affiliation with the Society shall clearly indicate his grade of membership.

Article IV. Code of Ethics

Section 1. Membership of any class shall be contingent upon conformance with the established principles of professional ethics.

Article V. Election, Resignation and Expulsion of Members

Section 1. The method of election to the various grades of membership shall be as set forth in the Bylaws.

Section 2. Any member in good standing may resign from the Society at any time as set forth in the Bylaws.

Section 3. Any member may for the good of the Society be suspended or expelled from the Society at any time as set forth in the Bylaws.

Article VI. Officers

Section 1. The officers of the Society shall be a President, a Vice-President, a Secretary-Treasurer, and an Editor. Officers shall be elected in the manner prescribed in the Bylaws for a term of one year with the exception of the Editor, whose term shall be two years.

Section 2. Election of officers shall be by secret mail ballot. On the ballot shall be printed the nominees for each office arranged in alphabetical order.

Section 3. The Standing Committee on Nominations shall nominate, in the manner prescribed in the Bylaws, two candidates for each office to be filled. Further nominations may be made by petition as set forth in the Bylaws.

Section 4. The officers shall assume the duties of their respective officers immediately after the close of the Annual Meeting following their election.

Section 5. No officer shall be eligible for election to the same office for two consecutive terms.

Section 6. In case of a vacancy in any office, other than the President's, the Executive Committee shall select a successor to serve until the close of the annual meeting following this appointment.

Article VII. Duties of Officers

Section 1. The President shall be the presiding officer at all the meetings of the Society, shall take cognizance of the acts of the Society and of its officers, shall appoint such Standing Committees and special committees as are required for the purposes of the Society, and shall delegate members to represent the Society. He may, at his option, serve on, and may be chairman of, any committee. He shall prepare an address to be given before the members of the Society at the Annual Meeting.

Section 2. The Vice-President shall assume the office of President in case of a vacancy from any cause in that office and shall assume the duties of President in case of the absence or disability of the latter. He shall also be responsible for all National Meetings of the Society.

Section 3. The Secretary-Treasurer shall assume the duties of the President in case of the absence of both the President and Vice-President. He shall have charge of the financial affairs of the Society and shall annually submit reports as Secretary-Treasurer covering the fiscal year, which he shall arrange to have published in the next regular issue of the Journal of the Society. Under the direction of the Council, he shall arrange for the receipt and disbursal of all Society funds. He shall cause an audit to be prepared annually by a public accountant at the expense of the Society. He shall give a bond, and shall cause to be bonded, all employees to whom authority may be delegated to handle Society funds. The amount of such bonds shall be set by the Council and the expense shall be borne by the Society.

Section 4. The Editor shall be in charge of the editorial business, shall submit an annual report of such business, shall have authority to solicit papers and material for the regular Society publication and for special publications, and may accept or reject material offered for publication. He may appoint associate, regional, and special editors.

Article VIII. Council

Section 1. The Council of the Society shall consist of the officers, the Past President, the Past Prior President, and all elected District Representatives.

Section 2. The Council shall be the governing body of the Society and subject to the provisions of the Constitution and Bylaws shall have full control and management of the affairs and funds of the Society.

Section 3. A joint meeting of the outgoing and incoming Councils shall be held at the call and under the Chairmanship of the newly elected President during or within seven days after the Annual Meeting of the Society. At this joint meeting the Councils shall hear reports from all Officers and Committees and review the activities of the Society for the past year. With the advice of the outgoing Council, the incoming Council shall conduct any necessary business and issue instructions or recommendations to any officer or committee, subject to the provisions of the Constitution and Bylaws. All committee chairmen shall attend this meeting, but, as Chairmen, shall have no vote.

Section 4. At the call of the President or a majority of the Council members, and after written notice to all Council members, the Council may meet at any time.

Section 5. A quorum at any meeting of the Council shall consist of six Council members.

Section 6. Unless otherwise provided by the Constitution, all actions by the Council shall require a majority vote of the members present.

Article IX. Executive Committee

Section 1. The Executive Committee shall consist of the President, the Vice-President, the Secretary-Treasurer, the Editor, and the Past President.

Section 2. When the Council is not in session the Executive Committee shall have full authority, subject only to prior instructions by the Council, to exercise all powers of the Council.

Section 3. All actions of the Executive Committee shall require a majority vote of all members of the Committee.

Section 4. The Executive Committee may vote on any matter either by mail or in person.

Article X. Meetings

Section 1. The Society shall hold at least one meeting of the members each year, this meeting to be known as the Annual Meeting. One session of this meeting shall be a Business Meeting, at which reports of the Officers and Committees shall be read and the result of the mail ballot for officers announced.

Section 2. The Annual Meeting shall be held at a time and place designated by the Executive Committee.

Section 3. Additional meetings of the Society may be called by the Executive Committee.

Article XI. Local Sections

Section 1. Local sections, consisting of members of the Society and other persons engaged in geophysics or a related field residing within an appropriate distance of a central point, may be organized as provided in the Bylaws.

Section 2. Each local section shall assist in carrying out the objectives of the Society within the territory assigned to the section by the Council.

Section 3. Each local section shall have one district representative if among its members there are less than seventy-five Honorary Members and Active members of the Society in good standing, two district representatives if more than seventy-five and less than one hundred fifty, or three district representatives if more than one hundred fifty.

Section 4. The district representatives shall be elected from among the Honorary Members and Active Members of the Society in good standing for terms stated and in the manner prescribed in the Bylaws and shall not be eligible for two consecutive terms.

Article XII. Districts

Section 1. The Council shall divide the area of the continental United States, not assigned to local sections, into not more than seven districts. Council may designate districts outside the area of the continental United States.

Section 2. Each district shall have for each seventy-five Active members of the Society, who are not members of a local section, one district representative, who shall be appointed by the President for a term of one year expiring at the close of the Annual Meeting.

Article XIII. Affiliated Societies

Section 1. The Council may arrange for affiliation of the Society with any duly organized groups or societies.

Section 2. The terms of affiliation must provide that the Society shall have the right to dissolve such affiliation at any time, subject only to the payment of any sums it may legally owe the affiliated group or society.

Article XIV. Committees

Section 1. In addition to the Executive Committee, there shall be appointed Standing Committees to further the purposes of the Society.

Section 2. The duties of the Standing Committees and the method of their appointment shall be in accordance with the Bylaws.

Section 3. The President may at any time appoint Special Committees for such purposes as he may deem fit.

Section 4. The terms of all Special Committees shall expire at the close of the Annual Meeting following their appointment.

Article XV. Business Manager

Section 1. The Council may employ a Business Manager for the Society and pay him such salary and other compensations from the Society's funds as they deem advisable.

Section 2. The Business Manager shall provide a bond appropriate in amount, the cost to be borne by the Society.

Section 3. The Business Manager shall, under the supervision of the Secretary-Treasurer, perform such duties as the Council may assign him.

Section 4. The Council may discharge the Business Manager at any time.

Article XVI. Review by Members

Section 1. All acts of the Officers, Council, and Committees of the Society shall be subject to review by the members.

Section 2. Proposals to change any decision, policy or procedure of any Officer, the Council, or any Committee shall be submitted in writing to the President and signed by at least twenty-five Honorary and Active Members in good standing.

Section 3. Upon receipt of such a petition with a sufficient number of valid signatures, the President shall advise the Council and the Officer or Committee involved.

Section 4. Should the Officer or Committee involved be unwilling to comply with the petition, it, together with a discussion by the proposer and the Officer or Committee involved, shall be published in the next issue of the Society's Journal.

Section 5. Within thirty days after publication in the Journal, the petition shall be submitted to the membership by mail ballot by the President. A majority of the ballots returned within thirty days after being mailed by the President shall be decisive. Should the vote favor the petition, it shall be complied with, within the limitations imposed by the Constitution and Bylaws, as promptly as practicable

Article XVII. Bylaws

Section 1. The Council shall make such Bylaws not in conflict with the Constitution, as it may deem necessary for the proper government of the Society. The Council may amend the Bylaws at the annual joint meeting by an affirmative vote of two-thirds of the members of the incoming Council present. All proposed amendments must, however, be published in the Society's Journal before being submitted to the Council.

Article XVIII. Amendments to the Constitution

Section 1. Amendments to this Constitution may be proposed by any ten members of the Society, by any Officer of the Society, or by a Constitutional Committee appointed by the President.

Section 2. Any proposed amendment shall be submitted to the President in time for publication in the Society's Journal prior to the Annual Meeting.

Section 3. At the annual joint meeting of the Council, all proposed amendments received since the previous annual meeting, shall be considered. Those receiving approval from a majority of the members of the incoming Council present shall be submitted by mail ballot, arranged by the Secretary-Treasurer, to the entire membership of the Society within sixty days. If a majority of the ballots returned within sixty days of their mailing favor the proposed amendment, it shall become effective at the expiration of this sixty days. All amendments shall be reported in the Society's Journal.

BYLAWS

Article I. Publications
Article II. Election of Honorary Members
Article III. Election of Active, Associate and Student Members
Article IV. Dues
Article V. Resignation of Members
Article VI. Expulsion of Members
Article VII. Election of Officers
Article VIII. Local Sections
Article IX. Finances of Local Sections
Article X. Standing Committees

BYLAWS

(As amended to March 25, 1952)

Article I. Publications

Section 1. The Society shall publish a Journal entitled *Geophysics*.

Section 2. The Journal shall be published at intervals designated by the Executive Committee.

Section 3. All reports to the Society by its officers and committees shall be published in the Journal. All members of the Society shall be presumed to have due notice of all Society matters published in the Journal. Each issue shall contain a membership list of all Standing and Special Committees.

Section 4. Original papers, reviews, abstracts, notes or letters containing information deemed by the Editor to be of interest to the members of the Society shall be published in the Journal. The Editor shall be the sole judge of whether such material is to be published.

Section 5. The subscription rate of the Journal shall be $9.00 ($9.50 foreign) per year to nonmembers and $3.00 per year to members. The first $3.00 of the annual dues of each dues paying member shall be set aside for the payment of his subscription to the Journal. Members of affiliated Societies shall be entitled to receive the Journal upon payment of a fee equivalent to the dues charged to an associate member.

Section 6. The Council may at its annual joint meeting authorize the printing of special publications to be financed and distributed in a manner approved by the Council.

Article II. Election of Honorary Members

Section 1. The Standing Committee on Honors and Awards may submit to the President ninety days before the Annual Meeting the names of any person or persons they deem eligible to election as an Honorary Member. Their report shall explain the basis of their recommendation.

SECTION 2. The President shall submit copies of any such reports to all members of the Council not less than sixty days before the Annual Meeting.

SECTION 3. The Council members shall consider all such reports and vote by mail thirty days before the Annuel Meeting. Unanimous action by those voting shall be required to elect any person as an Honorary Member.

ARTICLE III. ELECTION TO ACTIVE, ASSOCIATE AND STUDENT MEMBERSHIP

SECTION 1. An applicant for election to Active, Associate or Student Membership shall submit to the Business Manager of the Society an application setting forth in detail his education and experience. The application shall list the names and present addresses of persons who can verify the statements given therein. It shall list not less than three Active Members or Honorary Members of the Society, in good standing, who are personally acquainted with the training or experience of the applicant. This application shall be open to inspection at any time.

SECTION 2. The Executive Committee may waive the requirement of references from members of the Society for geographical or other reasons, if the applicant is otherwise eligible and furnishes other satisfactory references.

SECTION 3. The Business Manager shall write to all references for verification of the applicant's statements. All replies from references shall be considdred confidential and shall not be disclosed except to the Executive Committee, without the references' prior written consent.

SECTION 4. The Business Manager, upon receipt of the replies from all references, shall submit to the Executive Committee the application and the replies from the references.

SECTION 5. Should the Executive Committee unanimously approve and sign the application, the applicant's name shall be published in the next regular issue of the Society's Journal for approval by the membership at large. If no objection to his election is received by the President within thirty days after this publication, he shall be pronounced elected. The Business Manager will notify the applicant. In the case of applicants for Student Membership publication is not required. The student member shall be pronounced elected when approved by the Secretary-Treasurer.

SECTION 6. An applicant for membership, upon being notified in writing of his election, shall pay full dues for the current year and upon making payment shall receive a membership card and the regular Society publications for the year of entrance. Unless payment of dues is made within thirty days by those living within the continental United States and within ninety days by those living elsewhere, the Executive Committee may rescind the election of the applicant.

SECTION 7. An Associate or Student Member may seek transfer to Active Membership by supplying added information to show that he has become eligible to election to Active Membership. The transfer shall be handled in the same manner as election to Active Membership. The Standing Committee on Membership may of its own initiative secure the necessary added information and submit it to the Executive Committee.

ARTICLE IV. DUES

SECTION 1. Honorary members shall not be required to pay dues and shall receive the Journal and other publications without charge.

SECTION 2. The annual dues of an Active or Associate Member of the Society shall be seven dollars and fifty cents ($7.50), which includes the cost of one subscription to the Society's Journal.

SECTION 3. The annual dues of a Student Member of the Society shall be four dollars and fifty-cents ($4.50), which includes the cost of one subscription to the Society's Journal.

SECTION 4. Annual dues shall be payable in advance on January 1 of the calendar year. A bill shall be mailed to each Active, Associate or Student Member before that date, stating the amount of annual dues and the penalty for default. The Society's Journal shall be withheld from members pending payment of dues, and Active Members failing to pay by ten days prior to the Annual Meeting shall have their votes in the annual mail ballot disqualified. Members in arrears shall lose all privileges of membership until such arrears are met.

Article V. Resignation of Members

Section 1. Any member of the Society may resign at any time. Such resignation shall be submitted in writing to the Council.

Section 2. Any member who resigns under the provisions of Section 1 of this Article ceases to have any rights in the Society and ceases to incur further indebtedness to the Society.

Section 3. Any person who has ceased to be a member under Section 1 of this Article may be reinstated by unanimous vote of the Executive Committee subject to the payment of any outstanding dues and obligations which were incurred prior to the date when he ceased to be a member of the Society.

Article VI. Expulsion of Members

Section 1. Any member more than two years in arrears shall be dropped from the Society by the Executive Committee.

Section 2. Any member who is dropped under the provisions of Section 1 of this Article ceases to have any rights in the Society and ceases to incur further indebtedness to the Society.

Section 3. Any person who has ceased to be a member under Section I of this Article may be reinstated by unanimous vote of the Executive Committee subject to the payment of any outstanding dues and obligations which were incurred prior to the date when he ceased to be a member of the Society.

Section 4. Any member who, after being granted a hearing by the Executive Committee, shall be found guilty of a violation of the established principles of professional ethics, or shall be found guilty of having made a false or misleading statement in his application for membership in the Society, shall be asked to resign from the Society by unanimous vote of the Executive Committee. The decision of the Executive Committee in all matters pertaining to the interpretation and execution of the provisions of this section shall be final.

Article VII. Election of Officers

Section 1. The Standing Committee on Nominations shall consist of the President, the Past President, and the Prior Past President.

Section 2. The Standing Committee on Nominations shall nominate two or more candidates for each office to be filled. They must secure the consent of all candidates nominated.

Section 3. The Standing Committee on Nominations must submit their ticket to the President in time for publication in the October issue of the Society's Journal.

Section 4. Prior to December 1, nominations in writing, signed by at least twenty Honorary Members or Active Members in good standing and accompanied by the written consent of the candidate, may be submitted to the President.

Section 5. Between December 1 and December 15, the Business Manager will prepare and mail to each member, eligible to vote, a ballot listing all candidates properly monimated for each office. The candidates shall be listed side by side. With each ballot, the Business Manager shall send an official envelope having the member's name on the back.

Section 6. The Standing Committee on Nominations shall appoint a Committee of Tellers to count the ballots.

Section 7. Each member voting may cast one vote for each officer and shall return his ballot to the Business Manager in the official envelope carrying on the outside the written signature of the member submitting the ballot. Only ballots so prepared by members in good standing, and received by the Business Manager at his officially recognized address not later than January 31 shall be valid.

Section 8. The Business Manager shall indicate which ballots are valid, and shall deliver all ballots unopened to the Tellers after February 1. The candidate receiving the greatest number of valid votes cast for an office shall be declared elected to that office. In case of a tie, the Standing Committee on Nominations shall decide by a secret vote which of the candidates shall be elected. Results of the mail ballot shall be communicated to all candidates by the Nominating Committee on or before February 15.

Article VIII. Local Sections

Section 1. Upon petition of twenty members in good standing residing within an appropriate distance of a central point, the Council may authorize the formation of a Local Section and assign a specific territoty to the Local Section. The Council may decline to authorize the formation of a Local Section when in its judgment such an organization would not be compatible with the interests of the Society.

Section 2. In the organizing meeting of the Section, all members of the Society residing in the territory assigned by the Council to the Section shall be eligible to vote.

Section 3. The Section shall be known as "The (name of place) Section of the Society of Exploration Geophysicists."

Section 4. The principal work of a Section shall be the holding of regular meetings for the presentation and discussion of papers of interest to its members.

Section 5. The Section shall adopt Bylaws which must be approved by the Council of the Society and shall be consistent with the Constitution and Bylaws of the Society.

Section 6. The election of District Representatives by the Local Sections shall be by secret ballot. The term of office of a District Representative shall be two years; however, if the Section is entitled to more than one Representative, one of the Representatives elected at the establishment of the Section or added as the result of subsequent growth of the Section, shall be elected for a one year term if this is necessary to prevent the terms of all District Representatives from expiring simultaneously.

Section 7. District Representatives shall be elected at least three weeks prior to the Annual Meeting of the Society and shall take office at the close of the Annual Meeting.

Section 8. The Secretary of the Local Section shall submit to the Secretary-Treasurer of the Society a report of each meeting of the Local Section or its governing board within two weeks after the meeting. He shall submit to the Secretary-Treasurer of the Society the names of all officers and committee members within two weeks after their election or appointment.

Section 9. Any Local Section which for two consecutive years has among its membership fewer than twenty members in good standing of the Society shall automatically be dissolved by the Council at its annual joint meeting. The Council may at any time dissolve any Local Section for reasons it deems good and sufficient.

Article IX. Finances of Local Sections

Section 1. The Society may, at the discretion of the Council, pay any portion of the necessary operating expenses of a Local Section up to the sum of the following amounts: (a) $100 per year; (b) $50.00 per meeting up to four meetings per year; (c) $0.50 per member of the Society.

Section 2. The Treasurer of the Local Section shall forward, from time to time, his application for such portions of the sum provided in Section 1 as may be needed to the Secretary-Treasurer of the Society, who will arrange for the issuance of a check for the requested amount to the Treasurer of the Local Section.

Section 3. Prior to the Annual Meeting, the Treasurer of each Local Section shall transmit to the Secretary-Treasurer of the Society, for approval by the Council, an itemized statement of the expenditure of the funds received from the Society during the preceding calendar year.

Section 4. Allocations to a Local Section for the year in which it is established shall be in proportion to the fraction of the calendar year remaining.

Section 5. The Local Section may levy dues or raise funds in any other manner, subject to the approval of the Council. Payment of local dues shall, however, not be a prerequisite to participation in any activity financed wholly or in part with funds received from the Society.

Article X. Standing Committees

Section 1. The Society shall have the following Standing Committees: (a) Standing Committee on Nominations; (b) Standing Committee on Membership; (c) Standing Committee on Honors and

Awards; (d) Standing Committee on Publications; (e) Standing Committee on Program and Arrangements; (f) Standing Committee on Education; (g) Standing Committee on Student Membership; (h) Standing Committee on Distinguished Lectures; (i) Standing Committee on Radio Facilities; (j) Standing Committee on Reviews; (k) Standing Committee on Publicity; and (l) Standing Committee on Annual Survey of Geophysical Activity.

SECTION 2. Each Standing Committee shall have a chairman, appointed by the President unless otherwise specified in these Bylaws. The Chairman shall submit a report to the President of the Society at such intervals as the Chairman may deem advisable but at least quarterly. He shall submit to the Council at its annual joint meeting a report covering the activities of the Committee since the previous annual meeting.

SECTION 3. The Standing Committee on Nominations shall consist of the President who shall be chairman, the Past President, and Past Prior President. Its duties shall be to nominate candiates for officers, appoint Tellers to count the ballots and to declare the election of the officers as prescribed in Article VII of these Bylaws.

SECTION 4. The Standing Committee on Membership shall consist of three active members appointed for a period of one year by the President immediately following the Annual Meeting. One of the members appointed shall have been a member the preceding year. The Committee shall prescribe the manner of soliciting applicants for membership.

SECTION 5. The Standing Committee on Honors and Awards shall consist of five active members, none of whom shall have been members of the Society less than five years. The senior member of the Committee shall retire after the Annual Meeting. Vacancies shall be filled by the President. The Committee shall recommend candidates for election to Honorary Membership to the Council. The Committee shall recommend to the Council the establishment of Honors and Awards and shall recommend candidates for all established Honors and Awards of the Society to the Council.

SECTION 6. The Standing Committee on Publications shall consist of five active members who shall serve a two year term concurrent with the Editor and who shall be appointed by the Editor. The Committee shall have the duty of advising and assisting the Editor. The Editor shall appoint the Chairman of this Committee.

SECTION 7. The Standing Committee on Program and Arrangements shall consist of the Local Representatives plus three to ten additional active members appointed for a term of one year by the Vice-President, who shall be Chairman. The names of the members of the Committee shall be published in the July issue of the Society's Journal. The Committee shall have the duty of assisting the Vice-President in arranging and holding the Annual Meeting.

SECTION 8. The Standing Committee on Education shall consist of five active members appointed for one year by the President. The Committee shall promote effective geophysical education.

SECTION 9. The Standing Committee on Student Membership shall consist of five active members appointed for one year by the President. The Committee shall encourage the interest of students in geophysics and the Society.

SECTION 10. The Standing Committee on Distinguished Lectures shall consist of six active members appointed for three years by the President. The two senior members of the committee shall retire after the Annual Meeting. The Chairman of the Committee shall be appointed for one year by the President. The Committee shall obtain Distinguished Lecturers in geophysics and plan and supervise tours by these Lecturers to the Local Sections of the Society and other participating organizations.

SECTION 11. The Standing Committee on Radio Facilities shall consist of from 5 to 15 active members appointed for one year by the President. The Committee shall, upon request from its Chairman, determine the opinions of the members of the geophysical industry concerning matters pertaining to the use of radio in geophysics.

SECTION 12. The Standing Committee on Reviews shall consist of from 5 to 10 members who need not be active members of the Society. The membdrs and the Chairman shall serve a two year term concurrent with the Editor and shall be appointed by the Editor. The Committee shall prepare reviews of current geophysical literature for publication in *Geophysics*.

SECTION 13. The Standing Committee on Public Relations and Publicity shall consist of a Chairman, appointed for one year by the President, and such additional members, appointed for one year by the Chairman, as he may deem desirable. The Committee shall advise the officers and Council of the Society concerning matters pertaining to Public Relations and shall prepare and arrange for the distribution of suitable publicity material for the press and radio.

SECTION 14. The Standing Committee on Geophysical Activity shall consist of four or more active members of the Society appointed for a term of one year by the President. The Committee shall conduct an annual survey of geophysical activities throughout the world. This report shall be presented before the Society at its annual meeting and published in the July issue of *Geophysics*. It may be made available for publication in leading trade journals for release at the time of the annual meeting.

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